Journal of the Royal Society of Western Australia

ISSN 0035-922X

MUSE
22 JUL

CONTENTS

Page

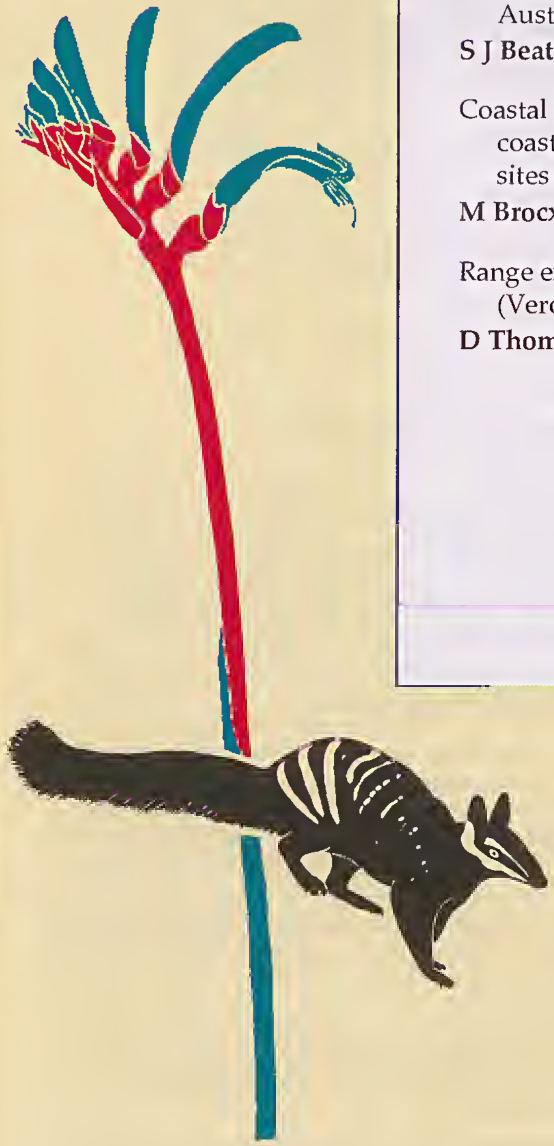
Spatial and temporal variations in the trapped terrestrial vertebrate fauna of the Hamersley Range, Western Australia
G G Thompson, S A Thompson & G R Finlayson 51

Teleosts, agnathans and macroinvertebrates as bioindicators of ecological health in a south-western Australian river
S J Beatty & D L Morgan 65

Coastal geoheritage: a hierarchical approach to classifying coastal types as a basis for identifying geodiversity and sites of significance in Western Australia
M Brocx & V Semeniuk 81

Range extension of the hard coral *Goniopora norfolkensis* (Veron & Pichon 1982) to the south-east Indian Ocean
D Thomson 115

Volume 93 Part 2
June 2010



The Royal Society of Western Australia

To promote and foster science in Western Australia

Patron
Her Majesty the Queen

Vice-Patrons
His Excellency Dr Ken Michael, AC
Governor of Western Australia

Professor Lyn Beazley AO FTSE MA PhD

COUNCIL 2009–2010

President	L Milne BSc (Hons) PhD
Immediate Past President	P O'Brien BSc (Hons) PhD
Senior Vice-President	V Semeniuk BSc (Hons) PhD
Junior Vice-President	A W R Bevan BSc (Hons) PhD
Hon Secretaries - Council	P Clifford BA
- Membership	J Rosser BSc (Hons) Grad Cert Ed Grad Dip App Sc PhD
- Proceedings	M Brocx BSc (Hons)
Hon Treasurer	P O'Brien BSc (Hons) PhD
Hon Editor	K Meney BA PhD
Hon Journal Manager	J E O'Shea BSc (Hons) PhD
Hon Librarian	M A Triffitt BA ALIA
Publicity Officer	V Semeniuk BSc (Hons) PhD
RSWA Archivist	A Pearce BSc MSc
Webmaster	G Deacon BSc (Hons) MSc PhD
Councillors	J Dook BPE DipEd PhD MAppSc K Oliver Dip App Chem BSc (Hons) BA M Van Keulen BSc (Hons) PhD J Wege Bsc (Hons) PhD K Wright BSc (Hons) PhD

The Royal Society of Western Australia was founded in 1914. The Society promotes exchange among scientists from all fields in Western Australia through the publication of a journal, monthly meetings where interesting talks are presented by local or visiting scientists, and occasional symposia or excursions on topics of current importance. Members and guests are encouraged to attend meetings on the third Monday of every month (March – November) at 7 pm, Kings Park Board offices, Kings Park, West Perth, WA 6005, or as advertised, in the RSWA Proceedings, Diary of Events.

Individual membership subscriptions for the 2009/2010 financial year are $60 for ordinary Members, $35 for Student Members and $32 for Associate Members. Library, company and institution subscriptions are $75 for the calendar year. Prices include GST. For membership forms, contact the Membership Secretary, c/- W A Museum, Locked Bag 49, Welshpool DC, WA 6986, or visit the website http://www.rswa.org.au.

The Journal of the Royal Society of Western Australia was first published in 1915. Its circulation exceeds 650 copies. Nearly 100 of these are distributed to institutions or societies elsewhere in Australia. A further 300 copies circulate to more than 40 countries. The Society also has over 350 personal members, most of whom are scientists working in Western Australia (see website http://www.rswa.org.au). The Journal is indexed and abstracted internationally.

Cover design: The four subjects symbolize the diversity of sciences embraced by the Royal Society of Western Australia. Mangles' kangaroo paw (*Anigozanthos manglesii*) and the numbat (*Myrmecobius fasciatus*) are the floral and faunal emblems of Western Australia, and stromatolites are of particular significance in Western Australian geology (artwork: Dr Jan Taylor). The Gogo Fish (*Mcnamaraspis kaprios*) is the fossil emblem of Western Australia (artwork: Danielle West after an original by John Long).

Journal of the Royal Society of Western Australia, 93: 51–64, 2010

Spatial and temporal variations in the trapped terrestrial vertebrate fauna of the Hamersley Range, Western Australia

G G Thompson[1,2], S A Thompson[2,3] & G R Finlayson[3]

[1] Centre for Ecosystem Management, Edith Cowan University,
100 Joondalup Drive, Joondalup, WA, 6027
✉ g.thompson@ecu.edu.au

[2] Terrestrial Ecosystems
10 Houston Place, Mount Claremont, WA, 6010
✉ scott@terrestrialecosystems.com

[3] Coffey Environments,
PO Box 4223, Victoria Park, WA, 6979
✉ graeme_finlayson@coffey.com

Manuscript received September 2009; accepted February 2010

Abstract

Fifty-four sites were surveyed in the Hamersley Range in March and November 2008 to assess temporal and spatial variability of terrestrial vertebrates and to compare this assemblage with published data for the Abydos Plain, an area to the north-east but still within the Pilbara bioregion. Appreciable seasonal variations in the trapped fauna were evident on the Abydos Plain and the Hamersley Range. Results indicate that single season surveys, and surveys that catch relatively few individuals, do not provide an adequate appreciation of the trappable fauna assemblages in the Pilbara. Similar to the Abydos Plain results, the vertebrate fauna assemblages in creek lines and the valley floor of gorges were different from that on flat plains and gently undulating areas, and in the Hamersley Range, the fauna assemblage was also different on rocky sloping terrain. Higher maximum daily temperatures in March compared with November seemed to be the main reason for a significantly higher number of individuals being caught, from which we concluded that surveys undertaken in the Pilbara during the cooler months would only record a proportion of the trappable vertebrate fauna in the area.

Keywords: Western Australia, Pilbara, fauna survey, trapping

Introduction

Temporal variation in the trapped terrestrial vertebrate fauna assemblage are apparent in many arid and temperate areas of Western Australia (How & Cooper 2002; Cowan & How 2004; Thompson & Thompson 2005), but there is a paucity of published information on temporal variations in the trappable fauna assemblages for the Pilbara, inland sandy deserts and the Kimberley. The only published data on temporal variations in fauna assemblages for the Pilbara are based on a Western Australian Museum survey in the late 1980s and early 1990s on the Abydos Plain which is to the north-east of the Hamersley Range. In the Abydos Plain study, How and Cooper (2002) reported that captures for the saxicoline rodent, *Zyzomys argurus*, showed little fluctuation over three years compared with *Pseudomys hermannsburgensis* and *Mus musculus* and How and Dell (2004) reported marked seasonal variation in the reptile assemblage during this same period. Both How and Cooper (2002) and How and Dell (2004) commented that fire had a significant effect on the relative abundance of mammals and reptiles living in *Triodia* habitats.

Vegetation and soil patterns normally have a marked influence on the spatial distribution of vertebrates at a local scale (How & Cooper 2002; Thompson *et al.* 2003; How & Dell 2004; Thompson & Thompson 2008; Gibson & McKenzie 2009). For example, Thompson *et al.* (2003) showed appreciable variation in the trapped reptile assemblage in 12 closely located habitats on the sand plain at Bungalbin, Western Australia. How and Cooper (2002) and How and Dell (2004) recorded marked differences in the mammal and reptile fauna assemblages based on soils and vegetation patterns on the Abydos Plain in the Pilbara and Gibson and McKenzie (2009) reported patterns of small mammal distribution in the Pilbara were mostly influenced by the substrate. Based on these data we anticipated both temporal and spatial variability in the trapped vertebrate fauna in the Hamersley Range.

Our objective here was to compare species richness between the Hamersley Range and the survey results for the Abydos Plain (How & Cooper 2002; How & Dell 2004) and to examine the extent of temporal and spatial variation in the trapped vertebrate fauna in the Hamersley Range.

The Abydos Plain survey is located in the Pilbara 1 (PIL1 – Chichester) IBRA subregion, which Kendrick and McKenzie (2001) described as undulating Archaean granite and basalt plains. The area is a relatively flat, stony plain drained by the Yule, Turner and De Grey Rivers and their tributaries (Figure 1). This bioregion is

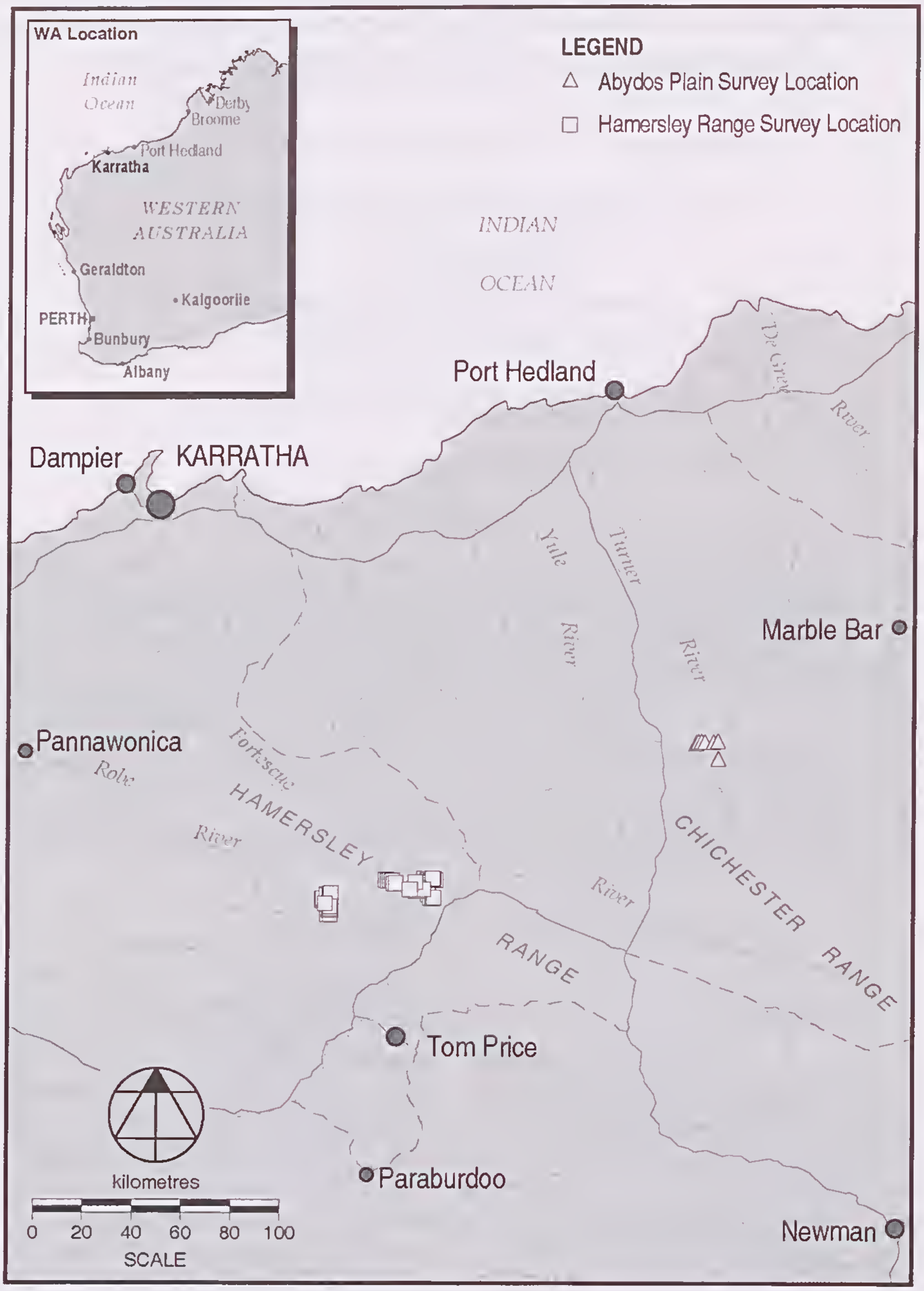


Figure 1. Survey sites in the Hamersley Range and the Abydos Plain.

mostly vegetated with spinifex and scattered acacia and eucalypt woodlands, with more dense vegetation along drainage lines. How and Cooper (2002) and How and Dell (2004) sampled eight sites over nine periods (March 1988, May 1988, September 1988, February 1989, April 1989, September 1989, March 1990, July 1990 and October 1990) using drift fences to direct fauna into PVC pipe or conical shaped pit traps. Type A and B aluminium box traps (Elliott design) were also set at each trapping site and baited with universal bait. Pit traps were open for 58 days of the 74 days over which trapping occurred.

Our Hamersley Range survey sites are located in the Pilbara 3 (PIL3 – Hamersley) IBRA subregion. Kendrick (2001) described this bioregion as a mountainous area of Proterozoic sedimentary range and plateaux dissected by gorges, which are vegetated with low mulga woodland over bunch grasses on fine textured soils in the valley floors. Fauna habitats that we surveyed included rocky substrate vegetated with spinifex, often with scattered trees and shrubs of varying densities, either on a flat, undulating or sloping terrain, with a mixture of bunch grasses and spinifex on loamy soils in flat or undulating areas, and ephemeral creek beds that supported a denser community of shrubs and trees. The latter category is mostly located in broad gorges, some with steep-sided hills or rocky faces. A number of survey sites contained vegetation that had been partially degraded by cattle.

Climate

The climate for this region is semi-desert, with most of the rain coming in summer from cyclonic events and thunderstorms. Figures 2 and 3 show the mean monthly average maximum and minimum temperatures and rainfall for Tom Price, which is about 60 km south of our Hamersley Range survey sites and Redmont which is about 20 km south of the Abydos Plain survey sites. Average maximum daily temperatures from December to February are in the high 30s to 40 °C dropping to the mid 20s in winter, with mean temperatures at Redmont being a couple of degrees higher than at Tom Price. Minimum daily average temperatures are typically 15 °C lower than the maximum temperatures. The rainfall patterns at these two weather stations were similar with most rain occurring between January and March, but Tom Price generally receives more rain during summer than Redmont (Figures 2 and 3).

Daily minimum ($F_{1,29}$= 18.1, $P < 0.01$) and maximum ($F_{1,31}$= 98.2, $P < 0.01$) temperatures at Tom Price, the nearest weather station to our survey sites, were significantly higher during our March survey (19.8 °C and 37.4 °C respectively) than during our November survey (16.4 °C and 33.9 °C respectively). It rained on two of the 14 survey days during March (12.4 and 0.4 mm respectively) and there was no rain during the November survey.

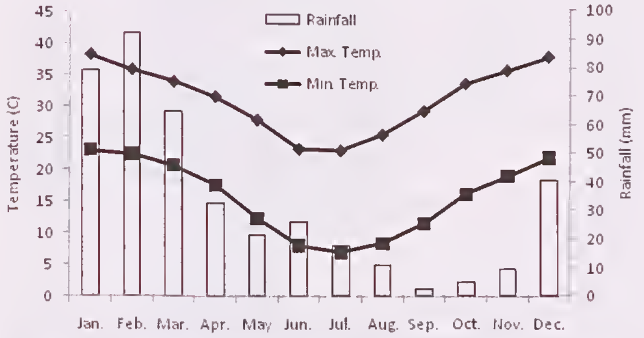


Figure 2. Monthly maximum and minimum temperatures and rainfall averages for Tom Price.

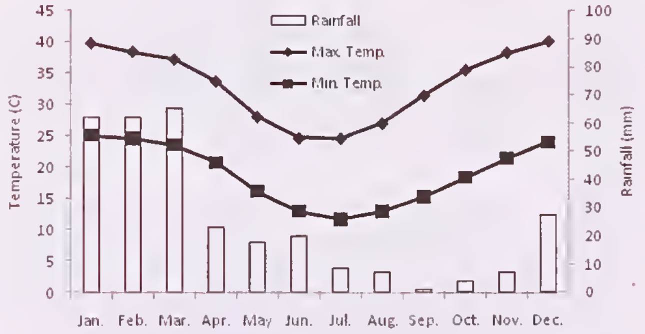


Figure 3. Monthly maximum and minimum temperatures and rainfall averages for Redmont.

How and Cooper (2002) reported significant seasonal and annual variations in rainfall at the Woodstock Station, but did not provide data on temperature or rainfall during their surveys periods.

Methods

Survey sites and trapping protocols

Fifty-four sites were sampled in the Hamersley Range, approximately 60 km north of Tom Price, Western Australia (Figure 1). Our analysis only addressed the trappable vertebrate assemblage, excluding any amphibians that were caught during the survey, as their capture was significantly influenced by the two rainfall events in March. Juveniles were identified when they were caught based on the known size of adults.

Trapping was undertaken in March 2008 and again in November 2008, with all traps being left open for seven days and nights for each survey. All traps were dug in during February/March 2008 and immediately closed until the set up program was completed. Each survey site contained four trap lines. Each trap line contained three 20 L PVC buckets, three 150 mm by 500 mm deep PVC pipes as pit-traps and three pair of funnel traps evenly spaced along a 30 m fly-wire drift fence (250 mm high; Figure 4). In addition, three aluminium box traps (two small; 330 X 100 X 90 mm and one large; 380 X 120 X 110 mm) were set adjacent to each drift fence. Aluminium box traps were baited with a mixture of sardines, rolled oats and peanut butter. Trap lines were arranged either parallel to each other, or end-on, depending on the availability of habitat and site access restrictions. For example, in some creek lines each trap line was located end-on 50–80 m apart and ran parallel to the direction of water flow to ensure that all traps were within a relatively homogenous habitat type. Buckets used as pit-traps contained two sheets of polystyrene in the bottom, funnel traps were covered with two shade covers and aluminium box traps were placed under bushes or covered with a shade cover to protect caught individuals from solar radiation.

For each survey site the combined trapping effort for March and November was 840 trap-nights (*i.e.* 168 bucket trap-nights, 168 pipe trap-nights, 168 aluminium box trap-nights and 336 funnel trap-nights) to give a total of 45,360 trap-nights of survey data. Almost all animals caught were identified and then immediately released near where they were caught, but far enough away from

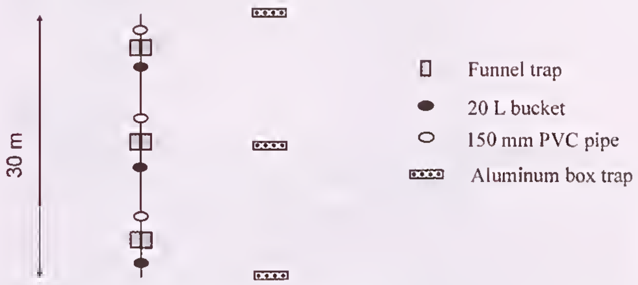


Figure 4. Trapping layout for each trap line.

Table 1

Percentage of individuals (shown as a decimal) caught for each species of the total number per cluster as shown in Figure 5 with the total number of individuals and species for each family

		Clusters as shown in Figure 5							
Family	**Species**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Total**
Dasuridae	*Dasykaluta rosamondae*					0.15	0.44		
	Dasyurus hallucatus	0.20	0.03						
	Ningaui timealeyi	0.61		2.33	4.00	0.75	0.79	1.12	
	Planigale spp.	3.24	0.47	18.60		4.48	3.02	2.25	
	Sminthopsis macroura	1.21	0.16			5.83	2.14	5.62	
	# Individuals	26	21	18	1	75	233	8	382
	# Species	4	4	2	1	4	4	3	5
Muridae	*Mus musculus*					0.30	0.36	2.25	
	Pseudomys desertor	1.42	0.31	1.16		2.84	5.32		
	Pseudomys hermannsburgensis	1.62	0.31	6.98		2.99	6.33		
	Zyzomys argurus	0.20	0.03	1.16	4.00	0.15	0.05		
	# Individuals	16	21	8	1	42	440	2	530
	# Species	3	3	3	1	4	4	1	4
Agamidae	*Amphibolurus longirostris*		0.19			1.35	1.62	14.61	
	Ctenophorus caudicinctus	6.88	0.22	5.81	4.00	5.83	1.23	1.12	
	Ctenophorus isolepis					0.15	2.36		
	Pogona minor	0.81	0.06	2.33		0.45	1.10		
	# Individuals	38	15	7	1	52	230	14	357
	# Species	2	3	2	1	4	4	2	4
Boidae	*Antaresia perthensis*						0.05		
	Antaresia stimsoni	0.20	0.25			0.45	0.47	1.12	
	# Individuals	1	8	0	0	3	19	1	32
	# Species	1	1	0	0	1	2	1	2
Elapidae	*Brachyurophis approximans*	2.23	0.37		4.00	0.60	0.38	1.12	
	Demansia psammophis	0.40				0.15	0.08		
	Demansia rufescens	0.40	0.03			0.30	0.25	1.12	
	Furina ornata	0.20	0.09			0.15	0.16		
	Parasuta monachus		0.03				0.14		
	Pseudechis australis	0.40				0.30	0.41		
	Pseudonaja modesta	0.40					0.16		
	Pseudonaja nuchalis		0.16				0.19		
	Suta fasciata			1.16			0.11		
	Vermicella snelli	0.40					0.03		
	# Individuals	22	22	1	1	10	70	2	128
	# Species	7	5	1	1	5	10	2	10
Gekkonidae	*Diplodactylus conspicillatus*					0.75	6.14		
	Diplodactylus jeanae	0.20					0.00		
	Diplodactylus savagei				4.00		0.03		
	Gehyra pilbara	0.40				0.15	0.03		
	Gehyra punctata	0.40				0.15	0.03		
	Gehyra variegata	0.40	0.19	1.16		0.15	0.44	3.37	
	Heteronotia binoei	10.93	0.37	1.16	8.00	5.98	2.93	5.62	
	Lucasium stenodactylus					0.15	0.11		
	Lucasium wombeyi	4.25	0.09		4.00	1.20	0.63		
	Nephrurus milii		0.03						
	Nephrurus wheeleri		0.03	2.33			0.36		
	Oedura marmorata		0.03						
	Strophurus elderi						0.11		
	Strophurus jeanae	0.20					0.69		
	Strophurus strophurus						0.05		
	Strophurus wellingtonae	0.61				0.15	0.71		
	# Individuals	86	24	4	4	58	447	8	631
	# Species	8	6	3	3	8	13	2	16

Table 1 (cont.)

		Clusters as shown in Figure 5							
Family	**Species**	**A**	**B**	**C**	**D**	**E**	**F**	**G**	**Total**
Pygopodidae	*Delma elegans*	0.20	0.03				0.03		
	Delma nasuta	0.20	0.09		4.00		0.08		
	Delma pax	1.01	0.06			0.60	0.38	1.12	
	Delma tincta						0.03		
	Lialis burtonis	1.21	0.03			0.30	0.36		
	Pygopus nigriceps	0.20	0.03			0.15	0.27		
	# Individuals	14	8	0	1	7	42	1	73
	# Species	5	5	0	1	5	6	1	6
Scincidae	*Carlia munda*	2.63	1.37			3.44	5.95	44.94	
	Carlia triacantha			2.33		0.15	3.56		
	Ctenotus duricola	6.88	0.03	8.14		12.11	2.49		
	Ctenotus grandis	1.01	0.62			1.94	6.66	2.25	
	Ctenotus helenae	1.62	0.72			11.81	13.19	5.62	
	Ctenotus leonhardii	0.40		2.33			0.38		
	Ctenotus nigrilineatus						0.08		
	Ctenotus pantherinus	10.93	0.44	9.30		12.86	6.61		
	Ctenotus rutilans	0.20					0.03		
	Ctenotus saxatilis	18.83	2.37	5.81	36.00	3.29	3.34		
	Ctenotus serventyi						0.03		
	Cyclodomorphus melanops	2.63	0.09			0.15	0.60		
	Egernia formosa				4.00				
	Lerista muelleri	0.20		2.33		0.30	0.27	1.12	
	Lerista verhmens	0.40		3.49	4.00	0.75	0.63	2.25	
	Lerista zietzi	0.81	0.12			0.30	0.03		
	Menetia greyii	2.02	0.09	1.16	8.00	0.75	1.07	2.25	
	Morethia ruficauda	0.81	0.16				0.05		
	Notoscincus butleri						0.25		
	Proablepharus reginae					0.30	0.22		
	Tiliqua multifasciata	0.20				0.90	1.04		
	# Individuals	245	193	30	13	328	1696	52	2557
	# Species	15	10	8	4	14	20	6	21
Typhlopidae	*Ramphotyphlops ammodytes*						0.08		
	Ramphotyphlops grypus	1.21	0.06	6.98		0.60	0.63		
	Ramphotyphlops pilbarensis		0.03			0.15	0.11		
	# Individuals	6	3	6	0	5	30	0	50
	# Species	1	2	1	0	2	3	0	3
Varanidae	*Varanus acanthurus*	5.67		6.98	12.00	3.29	0.88	1.12	
	Varanus brevicauda	0.40	0.06			7.32	7.15		
	Varanus bushi	0.40		2.33		0.60	0.33		
	Varanus eremius	0.81	0.03	2.33		1.35	3.21		
	Varanus panoptes	0.40	0.09	1.16		0.45	0.33		
	Varanus sp.	0.20				0.15	0.14		
	Varanus tristis	0.20		1.16		0.15	0.05		
	# Individuals	40	6	12	3	89	441	1	592
	# Species	7	3	5	1	7	7	1	7
	Total # individuals	494	321	86	25	669	3648	89	5332

the traps to avoid immediate recapture. A few individuals were vouchered with the Western Australian Museum or died in traps and were therefore not available for recapture. The trapping effort at each site was identical for the March and November surveys, making a direct comparison among sites and between surveys possible. Only reptiles and mammals caught in traps were used in this analysis.

Data analysis

Differences between data sets were compared using a *t*-test or an ANOVA when the variances were not equal and a hierarchical cluster analysis was undertaken in StatistiXL (http://www.statistiXL.com) using the Bray-Curtis dissimilarity coefficient with group-average linking for the combined March and November data to establish associations between site substrate and vegetation characteristics and trapped fauna assemblages. Cluster analysis was also used to generate separate dendrograms for the March and November data to demonstrate seasonal variations in the clustering of fauna assemblages. How and Cooper (2002) and How and Dell (2004) used NTSYSpc's (2000) Bray-Curtis dissimilarity index using the UPGMA method to group habitats based on the fauna assemblage composition.

The dendrogram from the cluster analysis showed various levels for grouping of survey sites based on the trapped fauna. To establish broad patterns of similarity among sites clustered in the dendrogram, we examined the substrate and vegetation at all sites looking for similarities and differences. Habitat variables considered were those that could be observed, such as vegetation type and structure, slope and surface substrate texture (*e.g.* loose stones, gravel, clay). We moved down the dendrogram to where similarities and difference in the substrate and vegetation among grouped sites could still be recognised and described. We used this grouping of sites as our fauna habitats.

Results

Fauna assemblage

A total of 5,332 individuals from 78 species were caught during the two surveys (Table 1). This included 912 mammals, 210 snakes and 4,210 lizards. On advice from the WA Museum, *Planigale* species could not be identified in the field (R. How pers. comm.) and as the only obvious difference among individuals was body size and we were unable to distinguish between juveniles and adults of different species, all individuals were grouped. It is possible that a few *Pseudomys chapmani* were misidentified as *P. hermannsburgensis*. Cooper (1993) indicated that differences in the size of the post hallucal pads on the pes of *P. hermannsburgensis* and *P. chapmani* can be used to differentiate these species. We found this diagnostic tool too difficult to use in the field and it is interesting to note that Cooper (1993) commented that a 10x hand lens should be used in identifying *Pseudomys* spp. from foot pads as pads are difficult to distinguish with the naked eye. We found no Pebble-mound Mouse mounds near our survey sites, so the number of individuals likely to have been misidentified would have been very low, if any. Five small varanids that were morphologically different to others in their size range and caught during the March survey were not able to be identified; these were recorded as *Varanus* sp. Photographs of these individuals were shown to a number of suitably experienced people including museum staff who were unable to identify them.

The mean number of individuals and species caught in each family at each site for the two survey periods is shown in Table 2. Skinks were the most frequently caught family, followed by geckos and varanids, and the least frequently caught were pythons and blind snakes.

Seven clusters of survey sites were recognised as fauna habitat types (Figure 5). Three of the clusters were single sites (C, D and G) and most sites fell into cluster F. Habitat characteristics for the seven recognised clusters are shown in Table 3. Cluster G was the most dissimilar, with the highest number of *Carlia munda* and *Amphibolorus longirostris* being caught at this location compared with all other sites. The major fauna attribute that differentiated cluster C from the other sites was the high number of *Planigale* species that were caught, and cluster D differed from other sites in that it had the least number of individuals (25) and species (13) caught at that site (Table 1).

A comparison between the dendrograms of survey sites for the March and November data sets shows little similarity (Figure 6), indicating appreciable differences in the vertebrate assemblages caught during these two survey periods.

Temporal differences

A total of 5,332 mammals and reptiles were caught during March and November, with more ($F_{1,106}$ = 129.4, $P < 0.01$) individuals being caught per site in March (mean 68.7 per site) than in November (mean 30.1 per site; Table 2). Also, more ($F_{1,106}$ = 69.6, $P < 0.01$) species were caught per site in March (19.3) than in November (13.5), with the combined survey period mean of 24.5 species per site. The total number of species caught in November (69) was higher than in March (66), and both were less than the total number of species caught for the combined data for both surveys (78). There was a significant difference

Table 2

Total number of individuals and species by family for the March and November surveys.

	Number of individuals			Number of species		
	March	November	Total	March	November	Total
Dasyuridae	224	158	382	4	5	5
Muridae	311	219	530	4	4	4
Agamidae	280	77	357	4	4	4
Boidae	28	4	32	1	2	2
Elapidae	104	24	128	9	8	10
Gekkonidae	434	197	631	11	14	16
Pygopodidae	42	31	73	5	6	6
Scincidae	1814	743	2557	18	19	21
Typhlopidae	33	17	50	3	2	3
Varanidae	438	154	592	7	5	7
Total	3708	1624	5332	66	69	78

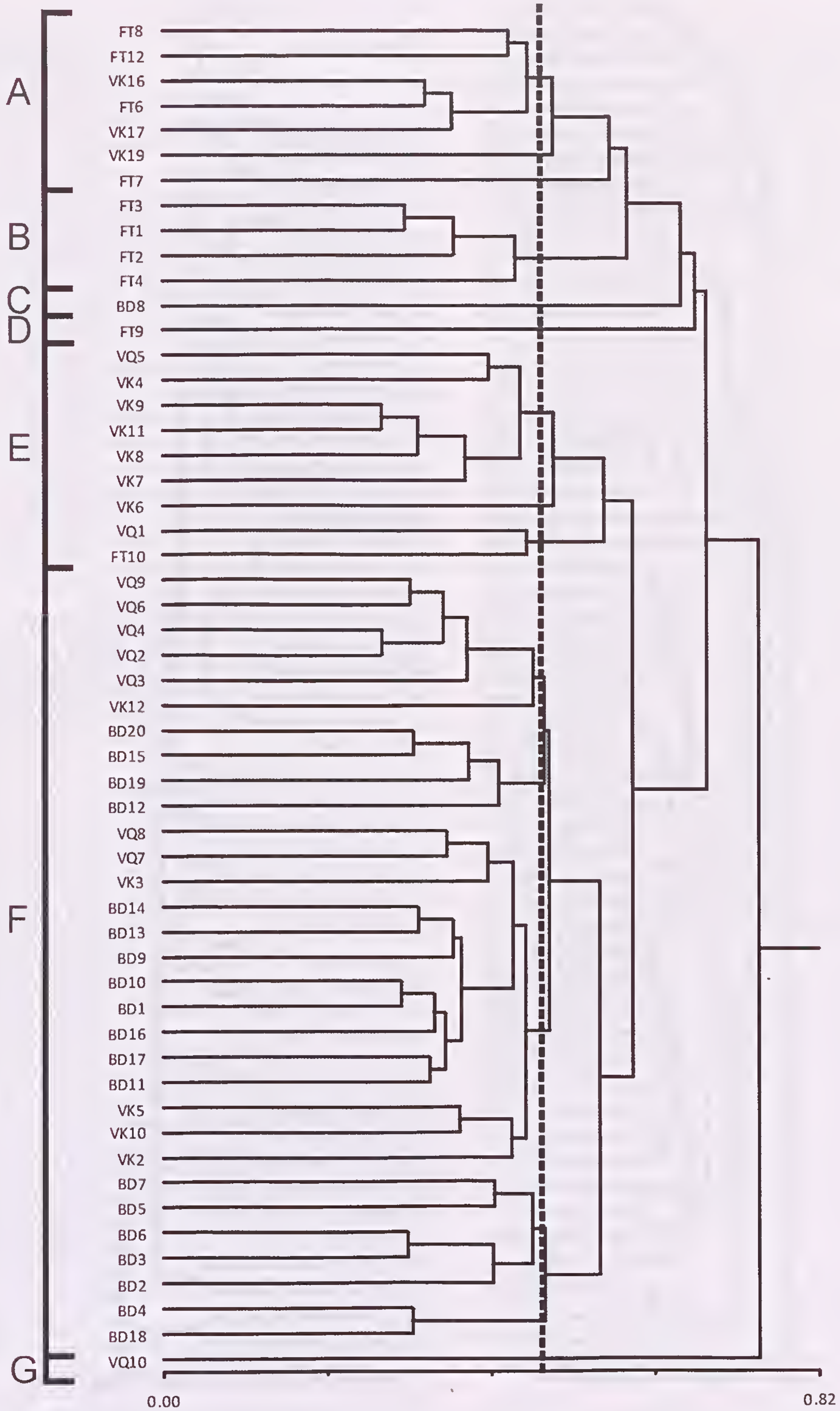


Figure 5. Dendrogram from a hierarchical cluster analysis of the fauna caught at 54 sites surveyed in March and November 2008 in the Hamersley Range with the level used to interpret seven clusters shown (dotted line).

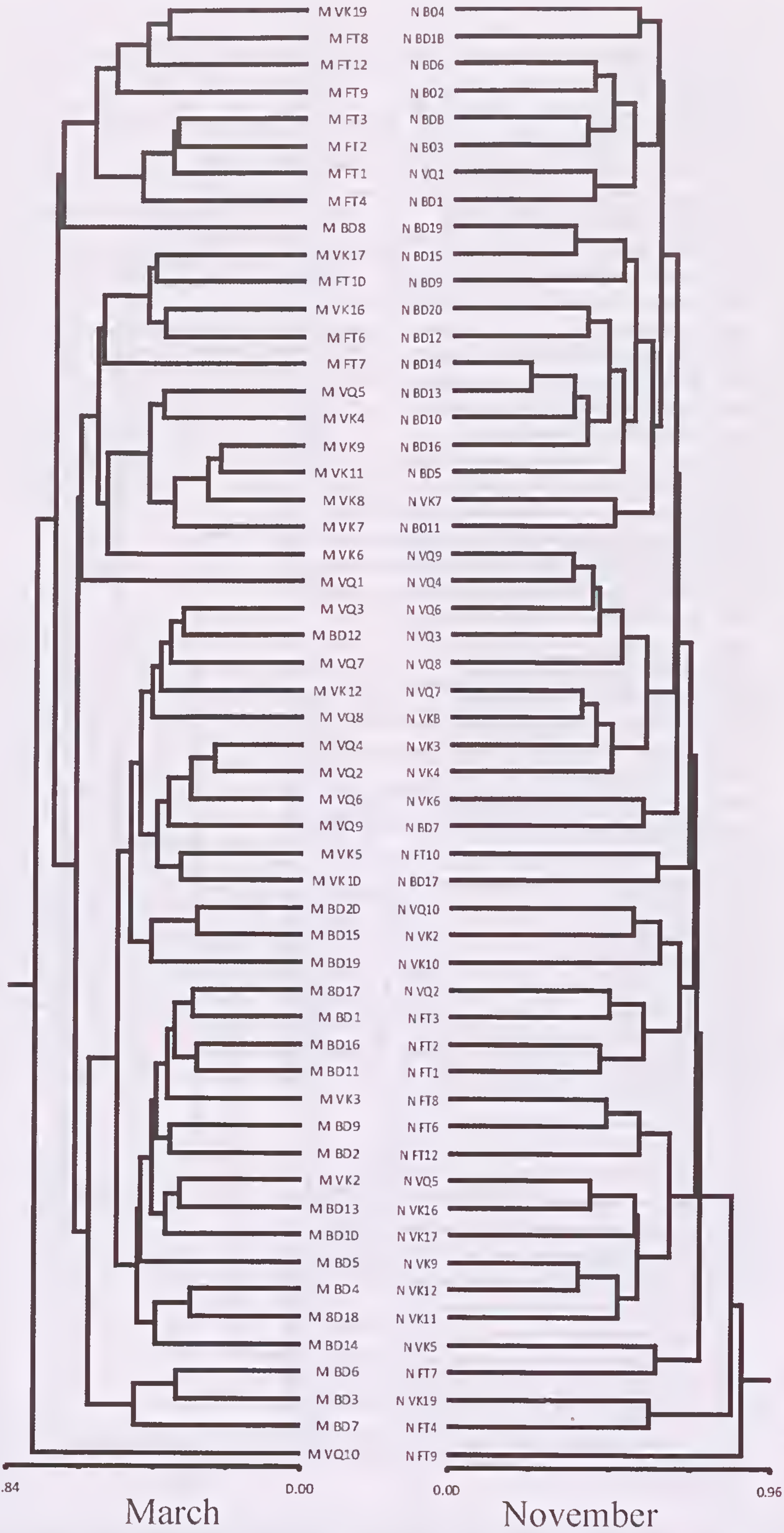


Figure 6. Comparison of the cluster analysis dendrograms for 54 sites surveyed in March and November 2008 in the Hamersley Range.

Table 3

Habitat descriptions for the clustered fauna survey sites as labelled in Figure 5.

Cluster	Habitat description
A	Sloping rocky terrain with low spinifex and scattered trees.
B	Gorge floor with a gravelly substrate that supported mature spinifex and shrubs to about 3m.
C	Flat area with mature spinifex on a clay substrate with lots of surface stones.
D	Steep rocky slope with low spinifex and lots of small stones on the surface.
E	Flat area with a clay substrate and lots of surface stones/rocks supporting scattered shrubs and small trees over spinifex.
F	Flat or gently undulating spinifex meadow with scattered shrubs and small trees with few surface rocks and stones.
G	Creek line with flowing water that comes to the surface in many places that supports tall eucalypts and melaleucas, shrubs and grasses adjacent to the water course on a creek bed of loose gravel or clay substrate.

($\chi^2_9 = 90.8$, $P < 0.01$) in the number of individuals caught in the various families between March and November, but no difference ($\chi^2_9 = 1.46$, $P = 0.99$) in the number of species that were caught. We recorded 134 hatchling/juvenile reptiles in March and 14 in November.

Discussion

The How and Dell (2004) data for the Abydos Plain sites incorporates individuals observed, so for comparative purposes we record the four additional species seen in the area but not trapped: *Aspidites melanocephalus, Liasis olivaceus barroni, Varanus pilbarensis* and *Varanus giganteus. Diporiphora valens, Caimanops amphiboluroides, Ctenophorus nuchalis, C. schomburkii, C. rubicundus, C. piankai, Diporiphora winneckei, Eremiascincus fasciolatus/richardsonii, Menetia surda, Lygisaurus foliorum* (*Carlia munda*?), *Nephrurus levis, Strophurus ciliaris, Heteronotia spelea, Acanthophis wellsi, Suta punctata, Ramphotyphlops waitii* and *Lerista frosti* (*L. jacksoni*?) have also been reported in the Hamersley Range by other authors (Texasgulf 1979; Johnstone 1980; Ninox Wildlife Consulting 1992; Biota 2008) but were not caught during our survey. The Hamersley Range therefore supports a diverse reptile fauna assemblage. By comparison, Thompson *et al.* (2003) reported large bioregional scale surveys in the Carnarvon Basin and Lake Eyre south catchment area recorded 76 and 57 species of reptiles respectively, and more localised surveys in or near the Great Victoria Desert (Red Sands), Uluru, Ewaninga, Simpson Desert, Great Victoria Desert (L Area), Bungalbin, Bold Park, Roxby Downs, Tanami Desert, Central Wheatbelt, Ora Banda and the Tanami Desert recorded 68, 37, 45, 36, 42, 46, 26, 27, 40, 42, 50 and 32 species of reptiles respectively. In addition to the nine species of mammals that we caught during the two survey periods, *Pseudantechinus* sp., *Pseudomys chapmani, Pseudantechinus macdonnellensis* (*roryi/woolleyae*?), *Sminthopsis ooldea* and *Tachyglossus aculeatus* have also been recorded in the area (Texasgulf 1979; Dunlop & Sawle 1980; Ninox Wildlife Consulting 1992; Biota 2008). The Hamersley Range includes flat plains, undulating hills, deep steep-sided gorges and valley floors, with substrates of sand, clay or rock, stony outcrops, breakaways and water courses that often support more dense vegetation. Vegetation is variable from large areas on stony substrate with little plant growth, to dense spinifex meadows or scattered and densely clumped shrubs and trees, so it is not surprising that the Hamersley Range supports high vertebrate species diversity.

Estimates of species richness based on trapping data are significantly affected by the trapping effort (Thompson & Thompson 2007). So when the trapping effort varies, as it does between our survey and the How and Cooper (2002) and How and Dell (2004) surveys of the Abydos Plain, the lower survey effort on the Abydos Plain is likely to have recorded a lower proportion of the species in the area. A species accumulation curve calculated using the methodology outlined in Thompson and Thompson (2007) for the combined data for our Hamersley Range sites indicated that we had caught 78 of a possible 83 trappable species (Figure 7). Above we indicated four other species that are known in the area that could have been trapped. How and Dell (2004) reported that there were 15 species of snakes and 51 species of lizards in the Abydos Plain area which compares with 17 species of snakes and 57 species of lizards that we either caught or observed opportunistically in the Hamersley Range. Opportunistic observation is not a reliable method for detecting some species, particularly geckos, but it was not possible to separate trapped and opportunistically recorded species in the How and Dell (2004) data, so we have included species observed but not trapped in our list to provide a comparison among fauna assemblages. How and Cooper (2002) caught nine species of dasyurids and five murids in their Abydos Plain survey compared with five dasyurids and four murids that we caught in the Hamersley Range. However, How and Cooper (2002) caught less than three individuals for seven of the dasyurids, with only two dasyurids (*Ningaui timealeyi* and *Dasykaluta rosamondae*) and two murids (*Mus musculus* and *Pseudomys hermannsburgensis*) relatively abundant. Of interest, Gibson and McKenzie (2009)

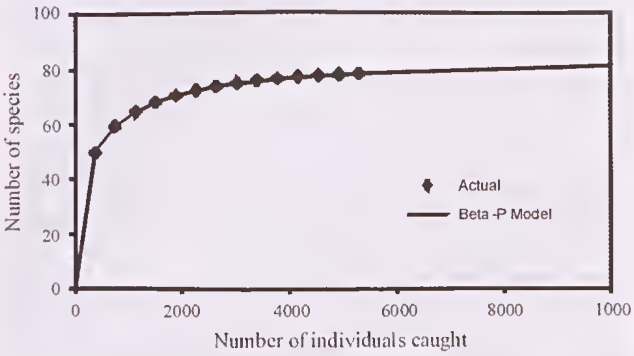


Figure 7. Species accumulation curve for all trapped vertebrate fauna for the March and November surveys

trapped 18 species of mammals with a body mass less than 50 g in the Pilbara biogeographic region. Gibson and McKenzie (2009) caught 3.5 individuals and 3.4 (± 0.1) small mammal species at each site. This is less than the 16.9 (± 2.30) individuals and 4.09 (± 0.56) species of mammals caught during our survey. Much of this difference can be attributed to the Gibson and McKenzie (2009) survey only using 125 mm PVC pipes as pit traps and a total of 140 trap nights at each site compared with a wider range of trap types and a higher survey effort in the Hamersley Range survey.

In summary, it is apparent that the high reptile diversity we report for a small section of the Hamersley Range is also present on the Abydos Plain. Mammal diversity in the Hamersley Range and the Abydos Plain were similar to that recorded in surveys in other areas in Western Australia (Thompson & Thompson 2008; Start *et al*. 2008).

Spatial variations

Based on our observations of the similarities and differences among clustered survey sites, we concluded that fauna assemblages in the Hamersley Range could be differentiated based on the slope of the terrain, substrate characteristics and the vegetation communities. Within the cluster of groups A, B, C and D, fauna on a steep rocky slope (*i.e.* cluster D) differed from that in cluster A (sloping rocky terrain), which differed from cluster B (*i.e.* gorge floor with gravelly substrate) and cluster C (*i.e.* flat with surface stones). The least number of species and individuals (*i.e.* 13 and 25 respectively) were caught on the steepest sloping survey site (*i.e.* Group D). The fauna assemblages in creek lines (*i.e.* groups G and B) differed from those in other areas. The fauna assemblage in a creek line that had flowing water either above or just below the surface and that supported melaleucas, taller eucalypts, dense shrubs and grasses (*e.g.* cluster G) was different from that in ephemeral creek lines that have a substrate of washed small gravel (*e.g.* cluster B). Fauna assemblages for sites grouped as E and F were on flat or gently undulating terrain, with the primary difference between the two groups being that cluster E sites contained lots of loose surface stones in contrast with cluster F sites that had few surface stones.

On the Abydos Plain the most dissimilar survey sites were those in riverine woodland along a creek line and the valley between steep slopes of calcrete mesas (How & Cooper 2002; How & Dell 2004). Small mammals showed well defined habitat associations, with *M. musculus* being mostly found in tussock grass banks of a creek, whereas *D. hallucatus, P. roryi, P. woolleyae* and *R. argurus* were found around granite tors, and *P. chapmani* were mostly found on rocky scree slopes (How & Cooper 2002). Gibson and McKenzie (2009) reported substrate characteristics (*i.e.* percent clay and silt, rockiness and ruggedness) were linked with small mammal species spatial distribution. They reported that *D. rosamondae, P. hermannsburgensis* and *Sminthopsis youngsoni* were more associated with sandy habitats, *D. rosamondae* avoided rugged areas and *P. hermannsburgensis* avoided rock outcrops. Gibson and McKenzie (2009) reported their *Planigale* sp. 2 was strongly associated with cracking and gilgaied clays, as was *S. macroura* but to a lesser extent as it was also found in a variety of habitat types. They suggested the two undescribed *Planigale* species in the Pilbara were separated on habitat type with *Planigale* sp. 2 preferring clay substrate and avoiding rocky habitat types and *Planigale* sp. 1 preferring the rugged substrate dominated by exposed bedrock. We only caught three of the larger *Planigale* sp., with two in cluster F (BD7 surface stones on a sandy-clay substrate vegetated with spinifex and scattered trees, VK5 surface stones on a sandy-clay substrate vegetated with spinifex and shrubs to about 2 m) and one in cluster A (VK17 stony slope with patches of spinifex and scattered trees). The smaller *Planigale* sp. was widely distributed. Gibson and McKenzie (2009) reported that *M. musculus* preferred the more fertile habitat such as those with a fine textured surface of loams and clays, but it was not strongly associated with any particular habitat in the Pilbara. Our data for the Hamersley Range recorded *M. musculus* in clusters E, F and G, which were flat or gently undulating plains with scattered small trees and shrubs over spinifex or the more densely vegetated creek line that had flowing water.

The reptile assemblage on the Abydos Plain was grouped based on those on deep loams with litter associated with fringing woodland vegetation along a creek line, those on a rocky breakaway and those on the deep sands of the Abydos Plain (How & Dell 2004). Some species that showed a strong preference for rocky habitats were infrequently captured on sandy substrates.

Digging in pit traps on rocky slopes (*e.g.* clusters A and D) in the Hamersley Range is logistically difficult, and it can also be difficult to do the same in creek beds (*e.g.* clusters B and G) that have dense vegetation and limited access. It is apparent that these habitat types support a different fauna assemblage to that which occurs in the adjacent areas. Often these assemblages will have fewer species and most often a subset of those in adjacent areas, so excluding these areas from a survey is unlikely to affect reported species richness for the entire survey area presuming sufficient survey effort has been deployed, but it will alter the understanding of the assemblage structure for the entire area.

Our observational data and records for other surveys in the Hamersley Range indicate that there are a couple of species that seem confined to habitats that are particularly difficult to trap (*e.g. V. pilbarensis, Oedura marmorata*), and others are in lower numbers (*A. melanocephalus, L. o. barroni*), or move infrequently and only small distances (*A. wellsi*) and can therefore easily go undetected.

Of particular interest was the *Nephrurus milii* that was caught in the floor of a steep-sided gorge that was a significant north-west range extension for this species (Thompson *et al.* 2009). This species is found in a variety of habitats elsewhere within its geographic distribution and is often abundant, but this was the first record for this species in the central and western end of the Hamersley Range.

Habitat generalists and specialists

Four species (*Dasykaluta rosamondae, Ctenotus isolepis, Diplodactylus conspicillatus, Lucasium stenodactylus*) were only found in clusters E and F, which are flat or undulating areas vegetated with scattered shrubs and small trees over spinifex. *M. musculus* was also only found in clusters E and F as well as cluster G, which is the creek line with flowing water that supports tall eucalypts and melaleucas, shrubs and grasses. *V. brevicauda* and *V. eremius* were mostly found on sandy loam substrates, but they were both often found in areas with a lot of surface stones. These habitats are appreciably different to the red sand ridge and swale systems of the inland deserts where *V. brevicauda* and *V. emerius* are abundant and wide-spread.

The most ubiquitous species in the Hamersley Range were *Heteronotia binoei, C. pantherinus* and *C. saxatilis*, all of which were caught at more than 51 of the 54 survey sites. The next most widely distributed species were *C. helenae, Planigale* spp., *Carlia munda, Pseudomys desertor, P. hermannsburgensis, C. grandis, V. brevicauda* and *C. duricola* which were trapped at more than 41 of the 54 survey sites. Other than *P. desertor* and *C. duricola*, all of these widely-abundant species were also caught on the Abydos Plain (How & Dell 2004) suggesting that they are relatively abundant in a range of habitat types in the Pilbara bioregion.

Assemblage structure

The Environmental Protection Authority's (EPA) Position Statement No 3 (2002) on terrestrial biological surveys indicated that best practice fauna assessments require the biodiversity of an area be evaluated at the ecosystem level. In the context of this statement and the rest of that document we interpret this to indicate that the EPA is seeking to identify and conserve fauna assemblages that are unique or have components that are of ecological significance (*e.g.* relatively high abundance of a particular conservation significant species or guild of species, or unusually high species richness or diversity). In order to make an assessment of a site or habitat type the fauna assemblage in the potential impact site should be compared with others within and beyond the bioregion to determine the extent to which it is unique and is of conservation significance. To date this is rarely done because there is limited comparative information available that enable a proponent to judge the conservation value of one fauna habitat against another within or beyond the bioregion, mostly because the sampling effort is either too low or so variable among surveys that comparative data among survey sites or fauna habitats are not available. Surveying 54 sites provided an opportunity to comment on what is a typical vertebrate fauna assemblage structure in the Hamersley Range.

The least trapped reptile families per site were pythons and blind snakes based on the number of individuals and number of species and the most abundant family was skinks (Table 2). Although not directly comparable because of different sampling efforts and protocols, these data are similar to that reported by Thompson *et al.* (2003) for numerous habitat types including sand ridges vegetated by spinifex, complex mosaic soils with mixed vegetation communities, and sand plains with shrubs and small trees. This pattern is also similar to that reported by How and Dell (2004) for the Abydos Plain.

Table 4

Mean (± 1SE) and the coefficient of variation expressed as a percentage (CV%) for the number of individuals and species caught per family in each survey site (N = 54) for the combined data for both surveys.

	Number of individuals			Number of species		
	Mean	SE	CV%	Mean	SE	CV%
Dasyuridae	7.07	0.610	63.4	2.13	0.121	41.8
Muridae	9.81	1.022	76.6	1.96	0.099	37.0
Agamidae	6.61	0.721	80.1	2.11	0.126	43.0
Boidae	0.59	0.139	172.0	0.33	0.065	142.7
Elapidae	2.37	0.267	82.9	1.74	0.167	70.0
Gekkonidae	11.69	1.000	62.8	3.31	0.198	43.8
Pygopodidae	1.35	0.174	94.4	1.07	0.121	82.6
Scincidae	47.35	2.505	39.9	8.39	0.296	25.9
Typhlopidae	0.93	0.163	129.1	0.574	0.078	99.2
Varanidae	10.96	0.839	56.3	2.907	0.176	44.5

The number of species and number of individual pythons and blind snakes caught was low, therefore it could be expected that the coefficient of variation expressed as a percentage (CV%) for these species would be high (Table 4). The lowest CV% was for skinks, which was to be expected as a total of 2,557 individuals from 21 species were caught during both surveys and they were widespread and caught in relatively high numbers at most sites. However, an average of only 8.4 species of skinks were caught at each survey site from a maximum number of 21 skink species (*i.e.* 40%) caught at all sites, which is a similar proportion to that for dasyurids (43%), rodents (49%), dragon lizards (53%) and goannas (42%), but higher than that for pythons (17%), front-fanged snakes (17%), legless lizards (18%), geckos (19%) and blind snakes (19%). These data indicate that for a single site surveyed in the Hamersley Range, you are likely to catch a higher proportion of the dasyurid, rodent, dragon lizard and goanna species present in the area than you are for pythons, front-fanged snakes, legless lizards, geckos and blind snakes due to both a lower number of species and the capture rate of only a few individuals at each site. An average of only 3.3 of the 17 species of geckos were likely to be caught in any survey site, which suggests that this family contains more habitat specialists than, for example, skinks. However, this difference may also have been an artefact of the sampling with the more widely foraging skinks being caught more often than geckos which perhaps move more slowly and cover less ground and are therefore less likely to be trapped.

Over 50% of the total number of reptiles and mammals caught came from six and two species respectively. In contrast, 36 of the reptile species and five of the mammal species contributed less than 5% of the total number of individuals caught. This pattern of a high proportion of species being in very low abundance and a few species in high abundance is similar to that reported by How and Cooper (2002) and How and Dell (2004) for the Abydos Plain and elsewhere (Downey & Dickman 1993; Masters 1996; Smith *et al.* 1997; Gibson & McKenzie 2009). The implication from this for future fauna surveys in the Pilbara is that a large number of individuals need to be caught in order to record a high proportion of the trappable species in the area. This concurs with the analysis of Thompson *et al.* (2007) who used species accumulation curves for numerous fauna sites for various habitats within Western Australia to come to a similar conclusion.

What was unusual about the trapped fauna in our survey of the Hamersley Range was the high proportion of *V. brevicauda* (235), *V. eremius* (91) and *Antaresia stimsoni* (28) that were caught in the March survey. When the catch for these three species was expressed as a percentage of the total number of individual reptiles caught (7.4%, 2.9% and 0.9% respectively), this percentage is higher than the proportion of varanids and pythons reported for many of the 14 surveys in Australia compared by Thompson *et al.* (2003). The next highest values that we could find for varanids was 3.1% for *V. brevicauda* and 2.5% for *V. eremius* in the Simpson Desert (Downey & Dickman 1993), and 3.6% for *V. eremius* in habitat not recently burnt near Uluru (Masters 1996). Both of these habitats were very different to that surveyed in the Hamersley Range. These three species are carnivorous predators but feed on prey items of different size (Geer 1989, 1997). These data would suggest there is an abundance of prey items to support this relatively high abundance of carnivores. This conclusion is also supported by the unusually high number of *P. australis* that were trapped and seen spotlighting during the March survey period.

The high proportion of *Planigale* species (21.7% of all mammals caught) in the data set was of interest. How and Cooper (2002) only recorded a single *Planigale* sp. on the Abydos Plain and Gibson and McKenzie (2009) reported *Planigale* sp. 1 and sp. 2 represented 3.1% and 14.2% of all the small mammals they captured across the Pilbara. We probably caught at least two species of *Planigale*, with one being much larger than the other. Our inability to distinguish juveniles of the 'larger' species from adults of the 'smaller' species meant that we could not be sure how many of each species were caught, although we did record individual *Planigales* caught as either 'large' or 'small'. We only caught three of the 'larger' species and it did not appear as if they were found in habitat types different to that of the smaller individuals.

Temporal differences

Average maximum and minimum monthly temperatures and rainfall for Tom Price from 1987 to 2008 are shown in Figure 2. Average temperature differences between March (mean max. 33.8 °C and min. 20.6 °C) and November (mean max. 35.6 °C and min. 18.9 °C) are only a couple of degrees, with November typically having a higher maximum and lower minimum. For our survey, the pattern was the reverse with mean ambient maximum and minimum temperatures during the March survey (37.4 °C and 19.8 °C) higher than during the November (33.9 °C and 16.4 °C) survey.

The number of mammals caught in March was significantly higher than during November, indicating that the abundance of mammals was higher in March than in November as we used an identical trapping protocol. How and Cooper (2002) indicated that the dasyurids that were commonly caught on the Abydos Plain during their three year investigation showed little fluctuation in abundance when compared with the rodents. They indicated that the changes in dasyurid numbers were more readily explained by the introduction of juveniles into the population. However, for *Dasykaluta rosamondae* in the first two years (1988–1989), numbers were higher in September than in February or March, whereas in 1990 when their abundance was high, the reverse was the case. Dickman *et al.* (2001) reported that for dasyurids, abundance fluctuations in the Simpson Desert were related to interactions between rainfall, resource availability and predation, with variation much less than for rodents.

For some rodents and dasyurids (*M. musculus*, *Ningaui timealeyi*, *P. hermannsburgensis* and *Zyzomys argurus*), How and Cooper (2002) indicated that September 1989 represented the highest number of captures on the Abydos Plain which is the reverse of what we recorded. These authors attributed this to major rainfall events 18 and seven months earlier. Dickman *et al.* (1999) reported dramatic fluctuations in the abundance of rodents after significant rainfall at three sites in arid Australia. In their study *M. musculus* numbers increased after two months of exceptional rainfall, whereas the other species increased in abundance 3–10 months after rain. The rainfall pattern at Tom Price in the two years prior to our first survey indicated substantial rainfall between

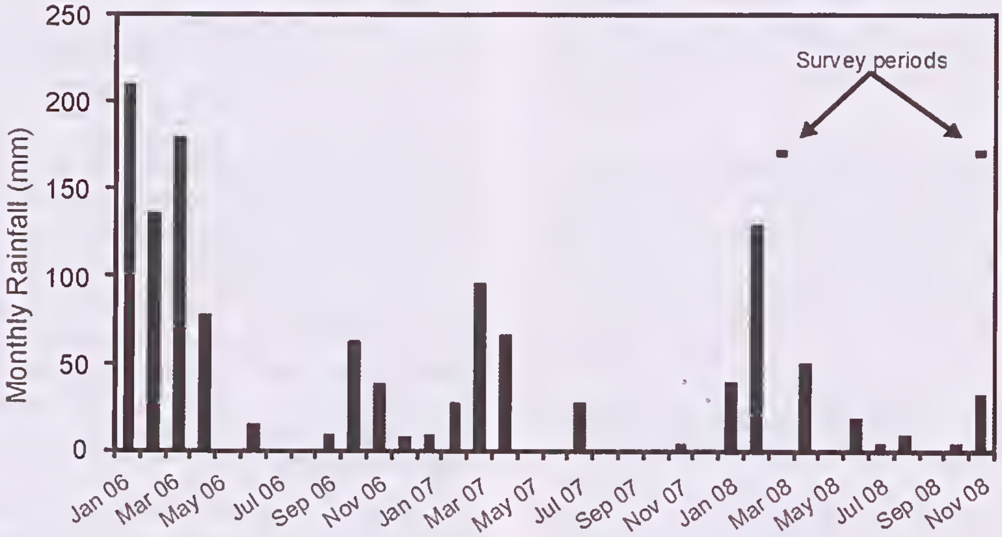


Figure 8. Monthly rainfall at Tom Price from January 2006 until December 2008.

January and April 2006, then a lesser amount in October/November 2006 and March/April 2007, with almost no rain then until January/February 2008 (Figure 8). Rainfall in the summer of 2006/07 was below average. The rainfall pattern in this part of the Pilbara is largely determined by the number of cyclones that pass across the coast with the subsequent rain bearing low pressure systems providing much rain over a few days. The lower number of mammals caught in November compared to March may reflect the relatively dry winter of 2008 (Figure 7), the rainfall that occurred during the March survey or recruitment of juveniles from the spring-summer breeding in 2007. If a major rainfall event was the primary contributor to the higher number of mammals being caught in March, as suggested by Dickman *et al.* (1999), then many of the individuals that were present in March disappeared by the November survey. Rainfall occurred on days five (0.4mm) and nine (12.4mm) during the March survey and there was no obvious increase or decrease in the trap success rate before or after these events so we discarded rain during the survey as a major contributor to the higher catch of mammals in March. A reduction in dasyurid numbers due to the death of breeding males after mating (*i.e.* spring and early summer; Tyndale-Biscoe 2005) may account for a loss of some individuals and recruitment of juveniles into the population post breeding would probably offset this loss of males. If this were the case, then there would be a reduction in the population of dasyurids in early summer and an increase later in summer as the juveniles become independent of their mothers and actively forage for themselves. Many male dasyurids would probably have died by our November survey and juveniles would be present in the March survey. This might account for some of the variation in dasyurid numbers. It is our view that much of the variation in caught abundance reflected activity patterns which related to ambient nocturnal temperatures as the reduction in dasyurids and murids from March to November was similar.

The number of reptiles caught during March was appreciably higher than in November 2008. How and Dell (2004) reported significant temporal variations in trapping success of the lizard communities on the Abydos Plain, with the highest number of species and individuals being recorded in summer, and fewer species and individuals being caught in spring and far fewer in April, May and July. Fires also influenced the abundance of reptiles with burnt areas having both lower diversity and evenness. Thompson and Thompson (2005) reported highest species richness and abundance of captures for reptiles in January, followed by December and September and then April in the Goldfields of Western Australia. Almost no reptiles were caught in their June surveys, as was expected for these ectotherms. In contrast, Cowan and How (2004) reported only a modest difference in the number of reptiles caught between March and October 1979/80 (142 *vs* 172) and no difference between the same months when surveyed again in 2001/02 (116 *vs* 115) during a survey of the Goongarrie area which is about 70 km north of the survey sites used by Thompson and Thompson (2005). In the spinifex dune-swale system about 40 km south of Alice Springs in the Northern Territory, James (1994) reported some species were caught in higher abundance in spring (*e.g. Ctenophorus isolepis, Diplodactylus conspicillatus*), while other species were caught in higher numbers during autumn (*e.g. Rhynchoedura ornata*) and one species was relatively constant (*Ctenotus pantherinus*). James (1994) reported that over half the reptile species had greater than a two-fold variation in abundance during five consecutive surveys undertaken in spring of 1985, 1986 and 1987 and autumn of 1986 and 1987.

For the Hamersley Range survey reported here, 20 reptile species were only caught during one of the two survey periods. Many of these were singletons or doubletons (*e.g. Egernia formosa, Ctenotus rutilans, Delma tincta*), but 15 *Demansia rufescens* and 11 *Furina ornata* were caught in March and none were caught in November. Other species that showed enormous temporal variation included *Diplodactylus conspicillatus* (222 *vs* 8), *Amphibolurus longirostris* (80 *vs* 7), *Varanus panoptes* (21 *vs* 0), *Varanus brevicauda* (235 *vs* 79), *Tiliqua multifasciata* (41 *vs* 4), *Lerista verhmens* (33 *vs* 3), *Ctenotus saxatilis* (257 *vs* 70), *Ctenotus pantherinus* (315 *vs* 80), *Ctenotus helenae* (439 *vs* 157), *Ctenotus grandis* (226 *vs* 57), *Lucasium wombeyi* (47 *vs* 9) and *Antaresia stimsoni* (28 *vs* 2). In addition to the reported trapping program, we also undertook a spotlighting program in the evenings and recorded appreciably more *Pseudechis australis* (27 *vs* 0) and *Antaresia stimsoni* (35 *vs* 4) in March than in November. It rained on two occasions in March and not at all in November, which may have contributed to the higher number of *P. australis* and *A. stimsoni* being active at night (Cowan & How 2004). We suggest an important reason for the higher number of individuals being caught in March compared with November is the higher ambient temperatures recorded in March. Thompson and Thompson (2005) reported a higher number of individuals and species being caught in spring than autumn in the Goldfields and if this pattern prevailed in the Hamersley Range then more individuals and species would have been caught in November than in March. We could find no data to indicate that periods of light rain with the associated increased humidity in non-tropical habitats would significantly increase the catch rate for March compared with November; although we have unpublished data to show catch rates for many species decrease immediately after a heavy rainfall event in the Goldfields. On a seasonal basis, ambient temperature is known to significantly influence reptile catch rates. This affect might also be evident on a day-to-day basis. The recruitment of juveniles into the population after the normal late spring – summer breeding period (Greer 1989, 1997) could also contribute to a higher catch rate in March than November, presuming that many of the juveniles did not survive the autumn to be present in the subsequent spring. We are confident that the higher number of reptiles caught in March was not just due to recruitment because of the higher number of long-lived, relatively slow growing species caught in March such as *V. eremius, V. brevicauda, P. australis, T. multifasciata* and *A. stimsoni* that were not juveniles. However, many of the *V. panoptes* caught during March were juveniles, as it is difficult to catch the adults in funnel or pit-traps. These data provide a strong case for undertaking multi-season surveys to fully understand the fauna assemblage present.

To further illustrate the importance of multi-season surveys to fully appreciate the assemblage structure and relative abundance of the fauna, we visually compared dendrograms calculated using the same protocols from a cluster analysis of the March and November data. An inspection of Figure 6 indicates the grouping of survey sites based on vertebrate catches in March and November differ. We concluded from this that the composition of the fauna assemblages caught at the 54 sites in March and November differed. If an environmental assessment was based solely on the March data, then the extraordinarily high number of *V. brevicauda* (235), *V. eremius* (91), *P. australis* (18) and *A. stimsoni* (28) caught could suggest that some of these fauna assemblages were regionally unique as we could find no other example of such a high proportion of these carnivorous predators being present in a trapped population. However, if we look at the November data, the number of *V. brevicauda* (79), *V. eremius* (42), *P. australis* (1) and *A. stimsoni* (2) caught were about what would have been anticipated based on data from other surveys in the Hamersley Range (Texasgulf 1979; Johnstone 1980; Ninox Wildlife Consulting 1992; Biota 2008) and elsewhere in the semi-arid region of Western Australia. These data confirm earlier investigations which indicate that single season surveys do not adequately represent the fauna assemblage in the Pilbara (Cowan & How 2004; How & Cooper 2002) or other regions of WA (Thompson & Thompson 2005) and probably elsewhere in Australia.

Acknowledgements: This fauna survey was undertaken to support an environmental impact assessment for the Fortescue Metals Group. We are very appreciative of the support of this company.

References

*Biota Environmental Sciences 2008 Marandoo Mine Phase 2 Seasonal Fauna Survey. Unpublished report for Rio Tinto, Perth.

Cooper N K 1993 Identification of *Pseudomys chapmani, P. hermannsburgensis, P. delicatulus* and *Mus musculus* using footpad patterns. Western Australian Naturalist 19: 69–73.

Cowan M A & How R A 2004 Comparison of ground vertebrate assemblages in arid Western Australia in different seasons and decades. Records of the Western Australian Museum 22: 91–100.

Dickman C R, Haythornthwaite A S, McNaught G H, Mahon P S, Tamayo B & Letnic M 2001 Population dynamics of three species of dasyurid marsupials in arid central Australia: a 10-year study. Wildlife Research 28: 493–506.

Dickman C R, Mahon P S, Masters P & Gibson D F 1999 Long-term dynamics of rodent populations in arid Australia: the influence of rainfall. Wildlife Australia 26: 389–403.

Downey F J and Dickman C R 1993 Macro- and microhabitat relationships among lizards of sandridge desert in central Australia. *In*: D Lunney & D Ayers D (eds) Herpetology in Australia: A Diverse Discipline. Transactions of the Royal Society of New South Wales, Sydney, 133–138.

Dunlop J N & Sawle M 1980 The small mammals of the eastern Pilbara and the Hamersley Range National Park. *In*: B G Muir (ed) A Fauna Survey of the Hamersley Range National Park Western Australia 1980, National Parks Authority, Perth, WA, 26–30.

*Environmental Protection Authority 2002 Terrestrial Biological Surveys as an Element of Biodiversity Protection. Position Statement No. 3. Environmental Protection Authority, Perth.

Gibson L A & McKenzie N L 2009 Environmental association of small ground-dwelling mammals in the Pilbara region, Western Australia. Records of the Western Australian Museum Supplement 78: 91–122.

Greer A E 1989 The Biology and Evolution of Australian Lizards. Surrey Beatty & Sons, Chipping Norton, NSW.

Greer A E 1997 The Biology and Evolution of Australian Snakes. Surrey Beatty & Sons, Chipping Norton, NSW.

How R A & Cooper N K 2002 Terrestrial small mammals of the Abydos Plain in the north-eastern Pilbara, Western Australia. Journal of the Royal Society of Western Australia 85: 71–82.

How R A & Dell J 2004 Reptile assemblage of the Abydos Plain, north-eastern Pilbara, Western Australia. Journal of the Royal Society of Western Australia 87: 85–95.

James C D 1994 Spatial and temporal variation in structure of a diverse lizard assemblage in arid Australia. *In*: L J Vitt & E R Pianka (eds) Lizard Ecology; Historical and Experimental Perspectives, Princeton University Press, New Jersey, 287–317.

Johnstone R E 1980 Herpetofauna of the Hamersley Range National Park. *In*: BG Muir (ed) A Fauna Survey of the Hamersley Range National Park Western Australia 1980, National Parks Authority, Perth, WA, 7–11.

Kendrick P & McKenzie N 2001 Pilbara 1 (PIL1 – Chichester subregion). *In*: A Biodiversity Audit of Western Australia's 53 Biogeographic Subregions in 2002. Department of Conservation and Land Management, Perth, 547–558.

Kendrick P 2001 Pilbara 3 (PIL3 – Hamersley subregion). *In*: A Biodiversity Audit of Western Australia's 53 Biogeographic Subregions in 2002. Department of Conservation and Land Management, Perth, 568–580.

Masters P 1996 The effects of fire-driven succession on reptiles in spinifex grasslands at Uluru National Park, Northern Territory. Wildlife Research 23:39–48.

*Ninox Wildlife Consulting 1992 Vertebrate Fauna Assessments (1975–1991) Marandoo Project Area. Unpublished report for Enviroscan, Perth.

Smith G T, Leone J & Dickman C R 1997 Small terrestrial vertebrate communities in remnant vegetation in the central Wheatbelt of Western Australia. Western Australian Naturalist 21: 235–249.

Start A N, Kendrick P G & McKenzie N L 2008 Biota of the Mandora system, Western Australia – Mammals. Journal of the Royal Society of Western Australia 91: 209–217.

*Texasgulf Aust. Ltd 1979 Marandoo Flora and Fauna. Unpublished report for Texasgulf, Perth.

Thompson G G & Thompson S A 2008 Spatial variability in terrestrial fauna surveys; a case study from the goldfields of Western Australia. Journal of the Royal Society of Western Australia 91: 219–28.

Thompson G G, Thompson S A, Withers P C & Pianka E R 2003 Diversity and abundance of pit-trapped reptiles in Australian arid and mesic habitats: Biodiversity for environmental impact assessments. Pacific Conservation Biology 9: 120–135.

Thompson S A & Thompson G G 2005 Temporal variations in reptile assemblages in the goldfields of Western Australia. Journal of the Royal Society of Western Australia 88: 25–36.

Thompson G G, Thompson S A, Withers P C & Fraser J 2007 Determining adequate trapping effort and species richness using species accumulation curves for environmental impact assessments. Austral Ecology 32: 570–580.

Thompson S A, Thompson G G & Finlayson G R 2009. Range extensions for the Barking Gecko, *Nephrurus milii* (Squamata: Gekkonidae). Journal of the Royal Society of Western Australia 92: 27–29

Tyndale-Biscoe H 2005 Life of Marsupials. CSIRO, Canberra.

*These reports are available from the Western Australian Environmental Protection Authority Library.

Journal of the Royal Society of Western Australia, 93: 65–79, 2010

Teleosts, agnathans and macroinvertebrates as bioindicators of ecological health in a south-western Australian river

S J Beatty & D L Morgan

Freshwater & Fish Group, Centre for Fish & Fisheries Research,
School of Biological Sciences and Biotechnology,
Murdoch University, WA 6150, Australia
✉ S.Beatty@murdoch.edu.au

Manuscript received September 2009; accepted February 2010

Abstract

Using standardised techniques to assess bioindicator groups from different food-web levels, the study aimed to provide an ecological baseline upon which monitoring of future changes in the aquatic ecological condition of the Warren River could occur. It also aimed to provide a review of the endemic freshwater fishes of south-western Australia in terms of their appropriateness as indicators of secondary salinisation. Fish and macroinvertebrate communities of the Warren River are described from historical and unpublished data and from sampling during 2006. The Warren River was found to be an important system in terms of freshwater fish conservation housing six of the eight endemic freshwater fishes of south-western Australia and is an important breeding and nursery ground for the Pouched Lamprey (*Geotria australis*). Many of these fishes are potential bioindicators of ecological impacts of salinisation of this and other rivers of the region. The relatively low SIGNAL 2 macroinvertebrate scores at the reference sites suggested that the communities in the main channel of the Warren River were generally those classified as tolerant of pollution. However, a small increase in the pollution sensitive taxa was recorded moving downstream with the most upstream (salinised) site (in the cleared section of the catchment) having the lowest composite and mean SIGNAL 2 score. The use of bioindicator groups from multiple levels of the aquatic food web should be more widely used in assessing and monitoring riverine health in south-western Australia; particularly with regards to the impact of secondary salinisation.

Keywords: Endemic teleosts; Pouched Lamprey; macroinvertebrate communities; aquatic bioindicators; salinisation

Introduction

Aquatic communities are commonly used as indicators of overall catchment condition (Fausch *et al.* 1990) specifically to determine and monitor biological integrity and overall aquatic ecosystem health and overcome the limitations of relying on physico-chemical indicators. These limitations include; inappropriate parameters being measured, synergistic interactions of contaminants being ignored, and spot-measurements not taking into account temporal variability in water quality (Karr & Dudley 1981; Barton & Metzeling 2004). Biological integrity is also more completely assessed by examining multiple levels of ecosystem integration (Simon 1999). Fish community assessment is commonly an important component of studies that aim to assess water quality, biological integrity and ecosystem health and their structure and function can integrate both the direct and indirect stresses on aquatic ecosystems (Simon 1999). The use of fish as indicators of the ecological impacts of secondary salinisation is particularly relevant as salinisation due to anthropogenic driven hydrological changes has been shown to structure fish assemblages (Higgins & Wilde 2005) and has been shown to cause considerable loss of freshwater fish populations (*e.g.*, Morgan *et al.* 2003; Hoagstrom 2009). Utilising both fish and macroinvertebrate communities as bioindicators is an effective way of incorporating multiple levels of food-webs in assessing and monitoring aquatic ecosystem health (*e.g.*, Harris 1995; Chessman 2003; Barton & Metzeling 2004).

Due to secondary salinisation associated with wide-scale clearance of vegetation for semi-intensive agriculture, only ~44% of flow in the largest 30 rivers in the south-west of Western Australia is fresh; the remainder being brackish or saline (Mayer *et al.* 2005). Trends in stream salinity and salt loads of rivers of the region are variable; with those catchments originating in cleared, lower rainfall areas (<1000 mm) usually having fresher flow in their lower reaches (due to freshwater inputs from forested streams and groundwater) compared to their headwaters (Mayer *et al.* 2005).

Secondary salinisation of aquatic ecosystems in south-western Australia due to human activities is known to have altered aquatic ecosystems by, for example altering vegetation and macroinvertebrate communities (Davis *et al.* 2003; Nielson *et al.* 2003; Boulton *et al.* 2007). South-western Australia has the highest proportion of endemic fishes and crayfishes of any Australian Division with 80 and 100% endemicity of these groups, respectively

(Morgan *et al.* 1998; Crandall *et al.* 1999; Allen *et al.* 2002). Within this region, salinisation of previously fresh habitats has also altered the fish assemblages, with salt-tolerant species becoming more prolific and non-salt-tolerant species often becoming restricted to fresher tributaries (Morgan *et al.* 2000, 2003). For example, secondary salinisation within the Blackwood River has resulted in much of the main channel becoming dominated by typically estuarine fishes such as the Western Hardyhead (*Leptatherina wallacei*) and Swan River Goby (*Pseudogobius olorum*), and also by the introduced Eastern Mosquitofish (*Gambusia holbrooki*) (Morgan *et al.* 2003; Beatty *et al.* 2006). Some of the freshwater fishes have been lost from most of the catchment and are now restricted to habitats that remain fresh, particularly those that receive groundwater supplements during dry periods (*e.g.*, Morgan *et al.* 2003; Beatty *et al.* 2006). Despite the known reduction in geographical ranges of many of these fishes due to decline in habitat and water quality, an initial assessment of their individual appropriateness as bioindicators has not previously been carried out.

The Warren River, in south-western Western Australia, has a catchment area of 4350 km^2 and a mean annual flow of ~400000 ML (Pen 1997). It is estimated that between 24 and 35% of the catchment has been cleared which has resulted in this once fresh system becoming increasingly salinised (Hodgkin & Clark 1989; Pen 1997; Smith *et al.* 2006). For example, salinities in the system exceeded 500 mgL^{-1} in the 1960s with average salinities in the 1990s reaching almost 900 mgL^{-1} (Collins & Barrett 1980; Smith *et al.* 2006). Although the Blackwood catchment is considerably more salinised than the Warren River, increasing salinisation of the Warren River and others in the region may result in similar changes to the prevailing aquatic fauna (Morgan *et al.* 2003; Beatty *et al.* 2006).

A desktop review of the significance of the aquatic fauna of the Warren River bioregion, and the adequacy of the reserve system in protecting it, was undertaken by Trayler *et al.* (1996). It highlighted the uniqueness of the aquatic fauna and concluded that the reserve system was important as it housed 86% of the total aquatic fauna of the bioregion. However, the study also stated that there were a number of threatening processes to those fauna that the reserve system alone could not negate. Threats to fauna within reserves (also ubiquitous throughout south-western Australia) included salinisation, land clearing, fire, erosion and deposition of sediment, in-stream barriers (*i.e.*, presence of dams) and the introduction of exotic fish (Trayler *et al.* 1996). Given these identified threats and uniqueness of the fauna in the catchment, there is a need to gather specific baseline information on aquatic bioindicator groups from multiple trophic levels to allow quantification of future changes in aquatic ecosystem health.

The first aim of this study was to gather baseline information on fishes, freshwater crayfishes and macroinvertebrates within the Warren River catchment from a detailed literature review and from sampling additional sites. The subsequent aim was to provide an assessment of these fauna in terms of their suitability as bioindicators of secondarily salinised habitats in this system and other rivers in south-western Australia.

Methods

Fish communities of the Warren River

In order to provide a comprehensive review of the fish fauna of the Warren River, published and unpublished data were examined. The following published and unpublished studies, together with captures during this study, were used and included data for over 75 sites: Christensen (1982), Pen *et al.* (1988, 1991a, b), Jaensch (1992), Morgan *et al.* (1998, 2002), Beatty & Morgan (2006) and Morgan & Beatty (unpublished data collected during various sampling occasions in the Warren River between 2002 and 2006). Distribution of the various study sites was mapped (using *MapInfo*™, Figure 1) and historical distributions of each species within the freshwaters of the Warren River catchment were determined (Figures 2–6).

During December 2006, five main channel sites on the Warren River were examined to determine the fish and crayfish species compositions. These sites included the junction of the Warren River with Wheatley Coast Rd (Site 5 – 116.2845°E, 34.3757°S), Gloucester Rd (Site 4 – 116.0232°E, 34.5052°S), Barker Rd (Site 3 – 115.8973°E, 34.5222°S), Larkin Rd (Site 2 – 115.9403°E, 34.553°S) and near the mouth of the Warren River (Site 1 – 115.8529°E, 34.6021°S) (Figure 1).

In order to ensure all resident species were recorded at each site, fish were captured using a combination of techniques; including a back-pack electro fisher (*Smith Root Model 12-A*), a 5 m seine net (2 mm mesh width) and fyke nets (two 5 x 0.8 m wings, 1.2 x 0.8 m opening and 5 m long pocket with two funnels all comprised of 2 mm mesh) set over a 24 hour period. Presence and relative abundances of freshwater crayfishes were also obtained using eight box-style freshwater crayfish traps (each baited with poultry layer pellets) set over a 24 hour period at each site. All native fish were measured to the nearest 1 mm total length (TL) and were immediately released. Introduced fishes were similarly measured and subsequently euthanased in an ice slurry and preserved in 100% ethanol. Native freshwater crayfish were measured to the nearest 1 mm orbital carapace length (OCL), sexed and released at the site of capture.

Environmental variables

At each main channel site (sites 1–5, see Figure 1) sampled for fish and macroinvertebrates (see below), three replicate measurements of water temperature, conductivity, pH and dissolved oxygen were taken 0.5 m below the water surface. Discharge and flow velocity profiles were also determined for sites 3–5.

Macroinvertebrate communities

In order to determine the macroinvertebrate communities at each reference site in the Warren River, three invertebrate sweeps each of two minutes duration were undertaken in three conspicuous habitats at each site. These habitats included open water, large woody debris, small woody debris, macroalgae (*Chara* sp.), submerged macrophytes, and emergent riparian vegetation. Each sweep was undertaken using a long-handled net (250 μm) deployed in a zigzag motion from

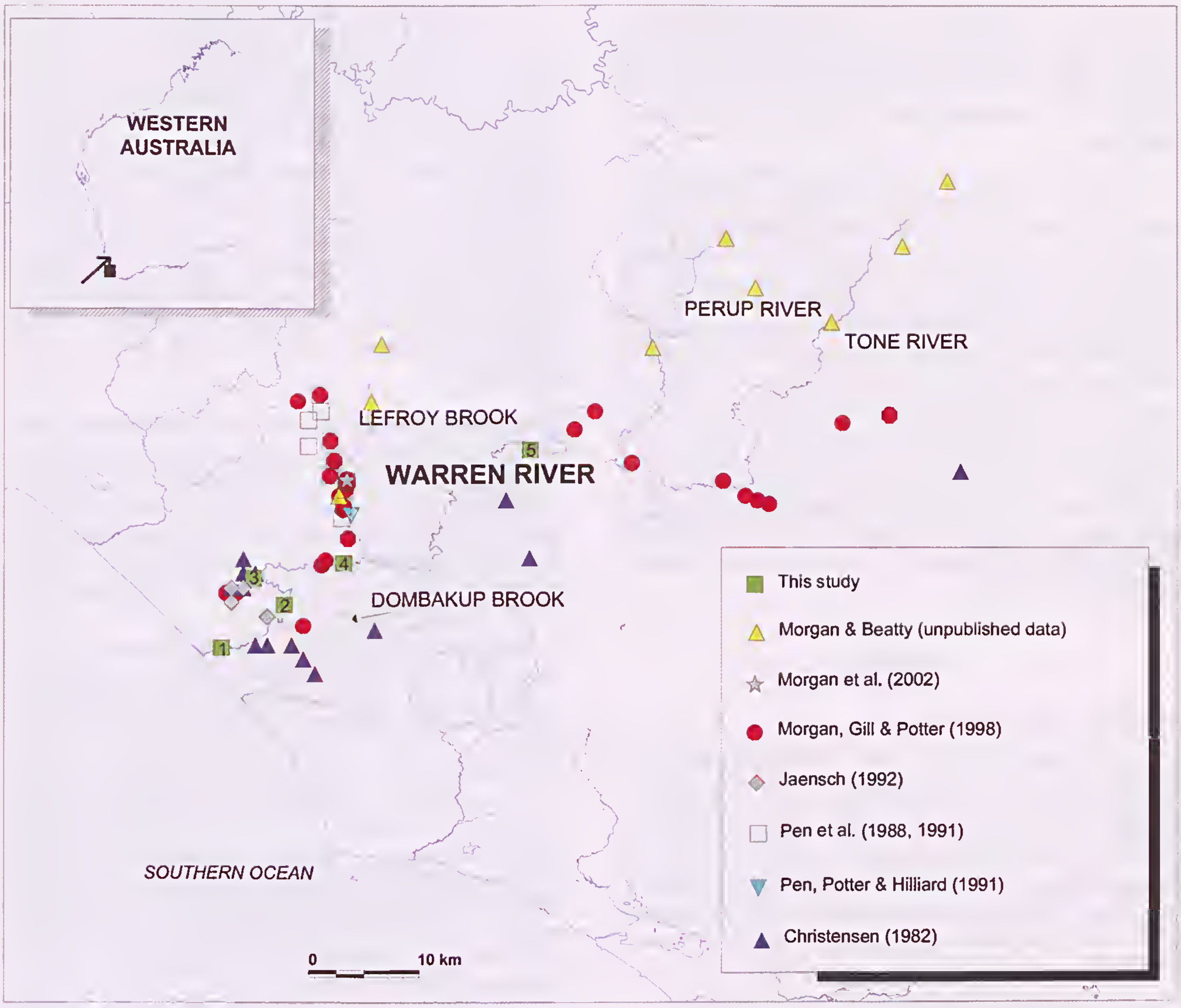


Figure 1. Sample sites from relevant studies utilised to determine the historical distribution of fishes in the Warren River catchment. Sites examined in the study are indicated (1–5).

the benthos to the water surface. The content of each sweep was immediately placed in 100% ethanol.

Invertebrate samples were examined under a dissecting microscope with the majority of taxa identified to family level. Mean relative taxonomic richness (*i.e.*, mean richness per habitat unit) at each site and the total relative taxonomic richness (*i.e.*, total richness across all habitats) of each site were determined. Relative (log-scaled) abundances of each group were recorded.

The macroinvertebrate SIGNAL 2 biotic index, used in the current study, grades invertebrate taxa (1–10) based upon their sensitivity to pollution with the higher the grade the more sensitive the taxon is to pollution (Chessman 2003). By averaging the SIGNAL grades across the taxa present at each site, an overall value is obtained that provides an indication of water quality at the site. Furthermore, SIGNAL 2 scores can also be weighted for abundance of each taxon; not just presence or absence (Chessman 2003). Therefore, it is a commonly used index for assessing aquatic ecosystem health.

The total unweighted SIGNAL 2 score was determined for each site (presence/absence, pooled habitats) as were both the mean unweighted and weighted (for relative abundance) SIGNAL 2 habitat scores at each site. The total unweighted score at each site was the average of the SIGNAL 2 grades of the taxa present at each site (pooled habitats). The mean unweighted score at each site was the mean SIGNAL 2 scores of the three habitats. To determine the mean weighted score of habitats at each site, the sensitivity grade of each taxon collected at each habitat was multiplied by the (log) abundance of that taxon collected, the products then summed for all taxa present in the habitat, and the total divided by the sum of the (log) abundances of all individuals present in the habitat (see Chessman *et al.* 2006). These mean weighted scores of the three habitats were then averaged for each site to give the mean weighted SIGNAL 2 score.

A number of taxa recorded in the Warren River did not have SIGNAL grades assigned (see results), these included; Calanoida and Cyclopoida (copepods), Podocopida (ostracods), Cladocera (water fleas), or Aranae (water spiders). Therefore, these were included in determining the relative taxonomic richness but excluded in determining the above SIGNAL scores at each site.

To further determine the level of differences and similarities in the macroinvertebrate assemblages between habitats and sites, multivariate analysis of invertebrate relative abundance was undertaken using multi-dimensional scaling (MDS) and Analysis of Similarity (ANOSIM) in the PRIMER v5.0 package (Clarke & Gorley 2001). ANOSIM involves the calculation of a test statistic, R, which is a measure of the average rank similarities of replicates within *a priori* designated groups (in this case habitats or sites) compared with the average rank similarity of all replicates among these groups. Thus, an R value of 0 indicates that there are no differences between these groups, whereas a value of 1 indicates that all replicates (invertebrate sweeps) within each habitat or site are more similar to those within those designated groups than they are to any of the replicates from the other groups.

Results

Environmental variables

Conductivity was low (769 – 1694 μS/cm) at all downstream sites when compared to the uppermost site (site 5) where mean conductivity was ~8000 μS/cm. Similarly, discharge was lowest at the most upstream site (~38 l/sec at Wheatley Coast Rd – site 5) and increased substantially at Gloucester Rd and Barker Rd (~1000 l/sec). There were no clear spatial trends in temperature (18.8 – 22.0 °C), pH (7.1 – 7.6) or dissolved oxygen (6.4 – 8.4 ppm).

Fishes of the Warren River

An examination of the published and unpublished literature, together with unpublished data of the authors and sites sampled during this study (see Figure 1) revealed that 13 species of fish and one agnathan were present in the freshwaters of the Warren River. This includes six of the South-west Coast Drainage Division's eight endemic freshwater fishes. The Freshwater Cobbler (*Tandanus bostocki*) was recorded at four of the five sites sampled during the current study (Figure 2). The Western Minnow (*Galaxias occidentalis*) was the most widespread, in terms of catchment area, of any native fishes captured being found in 35 sites (Figure 2). The Nightfish (*Bostockia porosa*) was also widespread throughout the catchment and is currently known from 39 sites and therefore ranked second in terms of site prevalence (Figure 3). The Western Pygmy Perch (*Edelia vittata*) was the most commonly encountered species in the system, being recorded at 45 sites, and is encountered throughout both the main channel and tributaries (Figure 3). The Black-stripe Minnow (*Galaxiella nigrostriata*) was extremely rare within the catchment and has only been reported from Four Mile Brook on Seven Day Rd (Morgan *et al.* 1998) (Figure 4). Importantly, the Western Mud Minnow (*Galaxiella munda*) may now have disappeared from sections of the Warren River (see Morgan *et al.* 2002) (Figure 4).

The Warren River also provides important breeding and nursery grounds for the anadromous Pouched Lamprey (*Geotria australis*) with larvae being recorded in Big Brook, Lefroy Brook and Dombakup Brook (Figure 5). Three estuarine fishes penetrate large distances up the main channel of the river, namely, the Western Hardyhead (*Leptatherina wallacei*), Swan River Goby (*Pseudogobius olorum*) and the South-western Goby (*Afurcagobius suppositus*) (Figure 5). Four species of fish have been introduced into the river, including Brown Trout (*Salmo trutta*), Rainbow Trout (*Oncorhynchus mykiss*), Redfin Perch (*Perca fluviatilis*, common in the system) and Eastern Mosquitofish (*Gambusia holbrooki*, the most widespread introduced fish in the system) (Figure 6).

Macroinvertebrates and decapods of main channel sites

Freshwater Shrimp (*Palaemonetes australis*) were prevalent at all five reference sites sampled in the current study (Figure 1). Smooth Marron (*Cherax cainii*) was recorded at four of the five sites (not being recorded at the most downstream site) and the Gilgie (*Cherax quinquecarinatus*) was recorded at all sites aside from Larkin Rd (Figure 1).

Taxonomic richness across sites ranged from 13 (Barker Rd) to 19 (Wheatley Coast Road crossing) and is consistent with previous studies of macroinvertebrate communities in this region (*e.g.*, Growns & Davis 1994) (Table 1). The most common taxon was the Chironomidae (non-biting midges), found in all habitats at all sites (Table 1). Other common taxa found at all five sites (and at 80% of habitats) were Caenidae (Ephemeroptera, *i.e.*, mayflies), Palaemonidae (Decapoda, freshwater shrimp), Cyclopoida (copepods in 60% of habitats), Leptoceridae, Hydroptilidae and Ecnomidae (tricopterans in 53, 47 and 53% of habitats, respectively) and Culicidae larvae (*i.e.*, mosquito larvae in 33% of habitats) (Table 1).

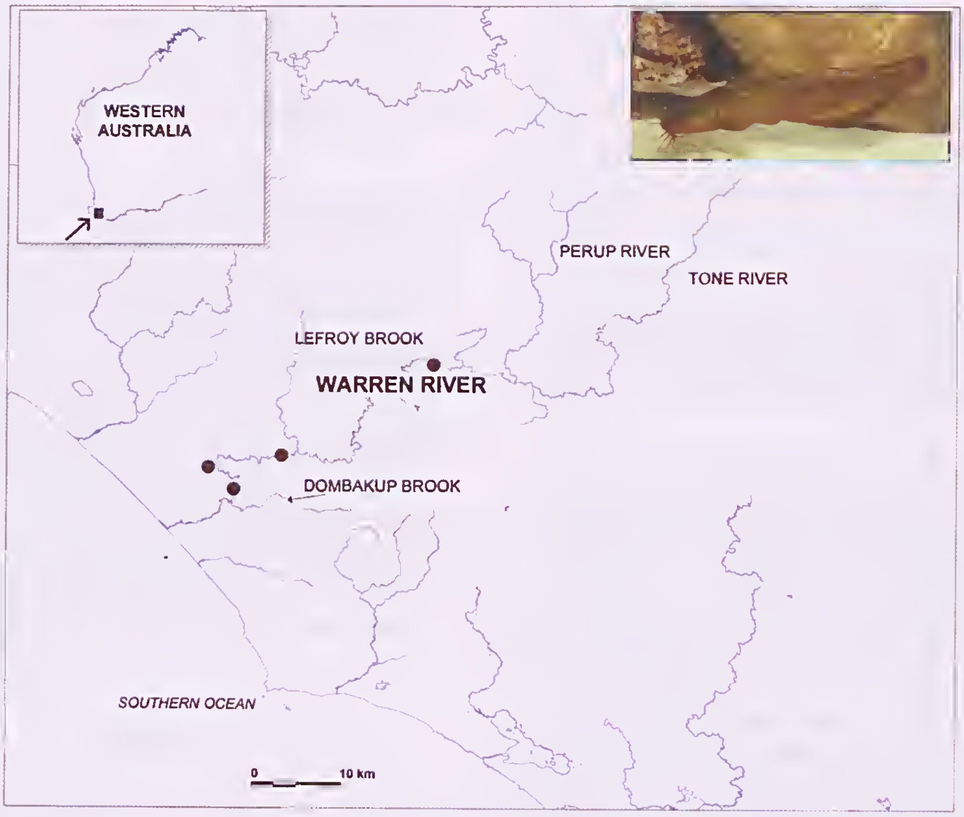
ANOSIM revealed that macroinvertebrate community composition was not significantly influenced by habitat type (Global R = 0.022, p = 0.447). However, from the MDS plot (Figure 7), the macroinvertebrate communities were relatively tightly grouped within habitats at three of the sites (*i.e.*, the mouth, Wheatley Coast Rd and Barker Rd) and ANOSIM revealed that macroinvertebrate community composition was significantly influenced by site (Global R = 0.258, p = 0.031). Pair-wise ANOSIM between sites found that the community composition at the most upstream (Wheatley Coast Rd) and the most downstream (mouth) sites were most distinct from the other sites, although only at a significance level of 0.1. For example the mouth site was different from the Larkin Rd (R = 0.82, p = 0.1), Barker Rd (R = 0.63, p = 0.1), and Wheatley Coast Rd (R = 0.53, p = 0.1), with the Wheatley Coast Rd site also being different from Barker Rd (R = 0.63, p = 0.1).

The relatively low composite macroinvertebrate SIGNAL 2 scores (ranging between 2.9 at the Wheatley Coast Rd site and 3.8 at the Barker Rd site), the mean weighted SIGNAL 2 score (ranging between 3.1 (±0.2) at the Wheatley Coast Rd site and 3.8 (±0.2) at the Barker Rd site) and unweighted SIGNAL 2 score (ranging between 3.1 (±0.2) at the Wheatley Coast Rd site and 4.1 at the Barker Rd (±0.2) and Larkin Bridge (±0.3) sites)

Table 1

Occurrence (Occ) and relative abundance (Log10) of macroinvertebrate taxa present in each habitat at each site in the Warren River in December 2006. Shown are: mean and total taxonomic richness, total unweighted SIGNAL 2 scores, and mean (±1 S.E.) weighted and unweighted SIGNAL 2 scores at each site. N.B. Habitat codes are: Open = open water, LWD = large woody debris, SWD = small woody debris, Algae = submerged *Chara*, Mac = submerged macrophyte, and Riprn = emergent riparian vegetation. No SIGNAL 2 scores are available for Calanoida and Cyclopoida, Podocopida, Cladocera, or Aranae.*=SIGNAL 1 score.

				Wheatley Coast Rd			Gloucester Rd			Barker Rd			Larkin Bridge			Mouth		
ORDER/SUB ORDER	FAMILY	Occ %	SIGNAL grade	Open	Algae	SWD	Open	Riprn	Mac	Open	Algae	LWD	Open	LWD	SWD	Open	LWD	Riprn
Calanoida		13		3			2											
Cyclopoida		60			4	3	3			3			2		2	3	3	3
Ephemeroptera	Caenidae	80	4	3	2	3	3	1	2		2	2	1			2	3	3
	Leptophlebiidae	47	8						1	3	2	1	1	1	3			
Diptera	Stratiomyidae	7	2			1												
	Culicidae	33	1			1		2			1			1				1
	Chironomidae	100	1	3	3	3	3	2	2	3	3	3	3	3	3	4	4	4
	Ceratopogonidae	33	4	1			1				1	1				3		
Coleoptera	Dytiscidae	20	2		1			1			1							
	Gyrinidae	13	4			1									1			
	Hydrophilidae	7	2													1		
Trichoptera	Leptoceridae	53	6	1	2	3	3				2		2			2		3
	Hydroptilidae	47	4					2		3	2	2			2	2		2
	Ecnomidae	53	4	1		2			2		2		1	1		2	2	
Decapoda	Palaemonidae	80	4	1	3	3		2	3	1	2	2		1	2		2	1
Isopoda	Amphisopidae	13	1	1	1													
	Cirolanidae	13	2											1	3			
Podocopida	Cyprididae	47		1	4	3							2	1	1			1
Cladocera	Daphniidae	27					1			1						3	2	
	Macrothricidae	7											1					
Araneae		33						1			1		1			1		1
Acarina (Hydracarina)	Pionidae	7	6														1	
Mollusca	Hydrobiidae	13	4		1	1												
	Physidae	7	1		1													
	Planorbidae	20	2					1						1				1
Amphipoda	Ceinidae	13	2		2	3												
	Perthidae	7	4			2												
Anisoptera		27	3	1	1								1		1			
Oligochaeta	Megadrile worms	13	2													3	1	
Mean (and total) richness per site				11.7 (19)			6.3 (15)			7.7 (13)			9.0 (16)			9.7 (16)		
Total SIGNAL 2 score				2.9			3.6			3.8			3.6			3.3		
Mean weighted SIGNAL 2 score				3.1 (0.2)			3.3 (0.5)			3.8 (0.2)			3.4 (0.4)			3.2 (0.1)		
Mean unweighted SIGNAL 2 score				3.1 (0.2)			3.5 (0.6)			4.1 (0.2)			4.1 (0.3)			3.9 (0.3)		



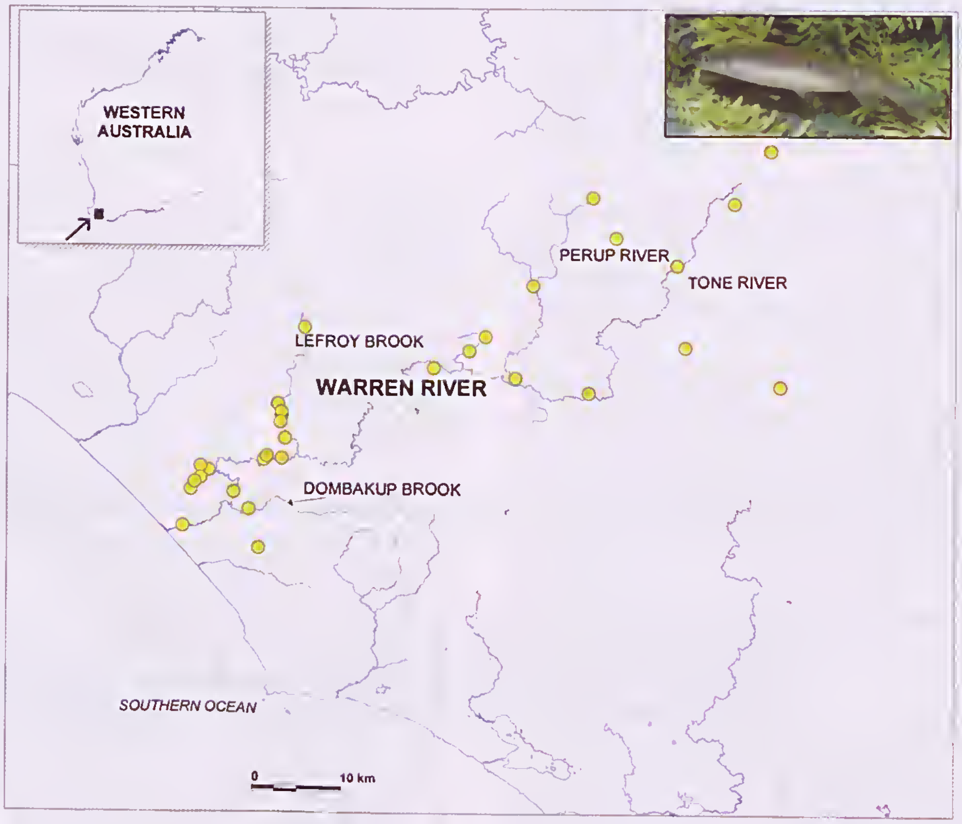
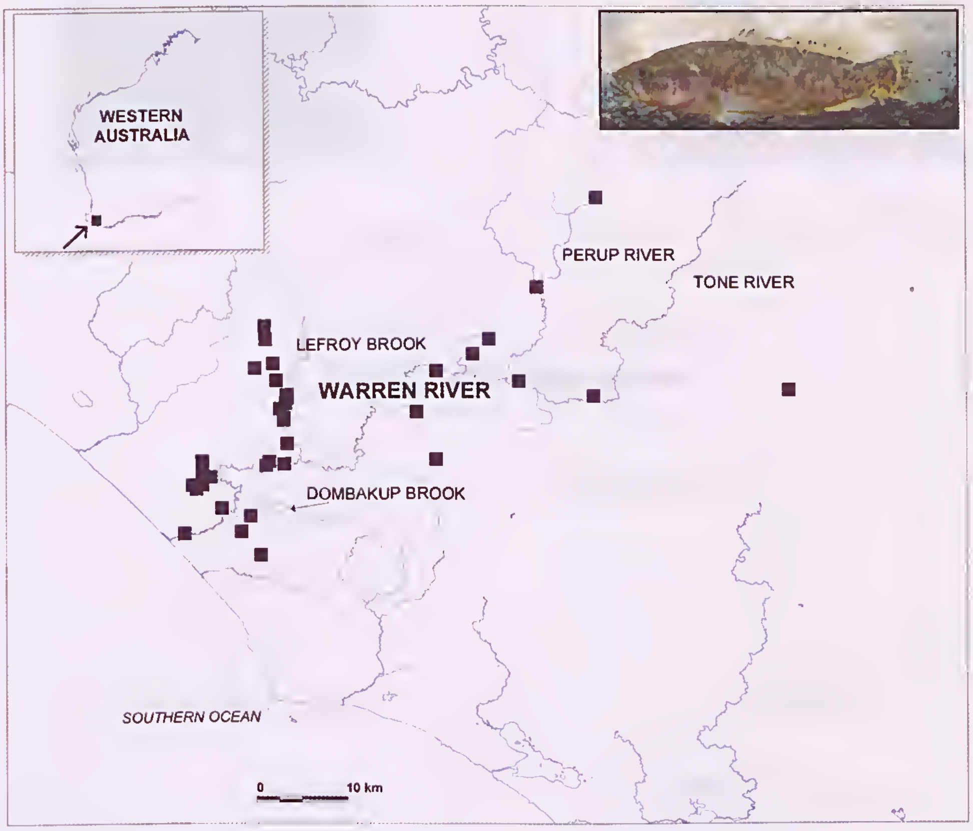


Figure 2. Distributions of the Freshwater Cobbler (top, photo M Allen) and Western Minnow (bottom, photo D Morgan) in the Warren River catchment.



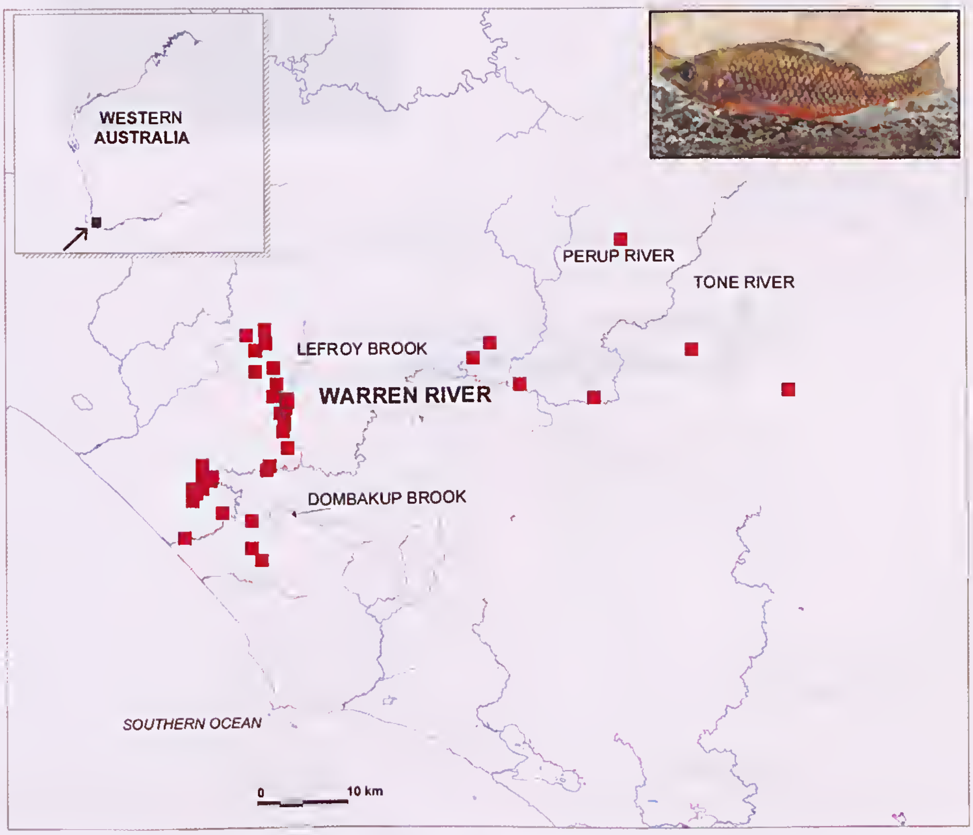
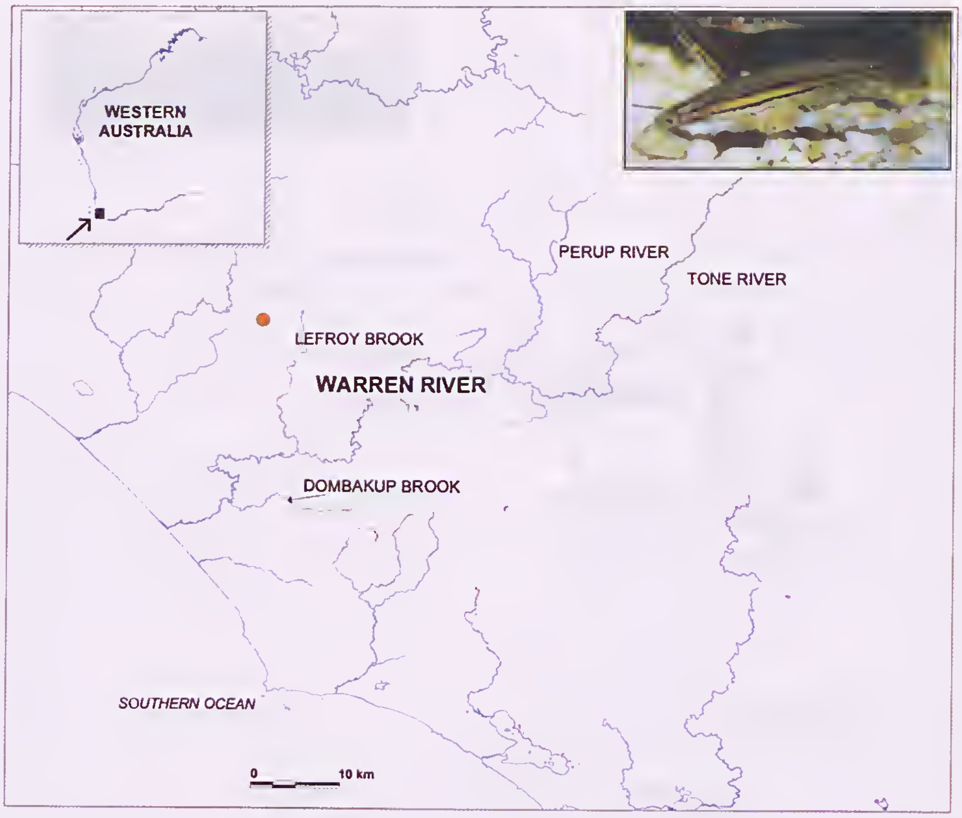


Figure 3. Distributions of the Nightfish (top) and Western Pygmy Perch (bottom) in the Warren River catchment. Photos S Beatty.



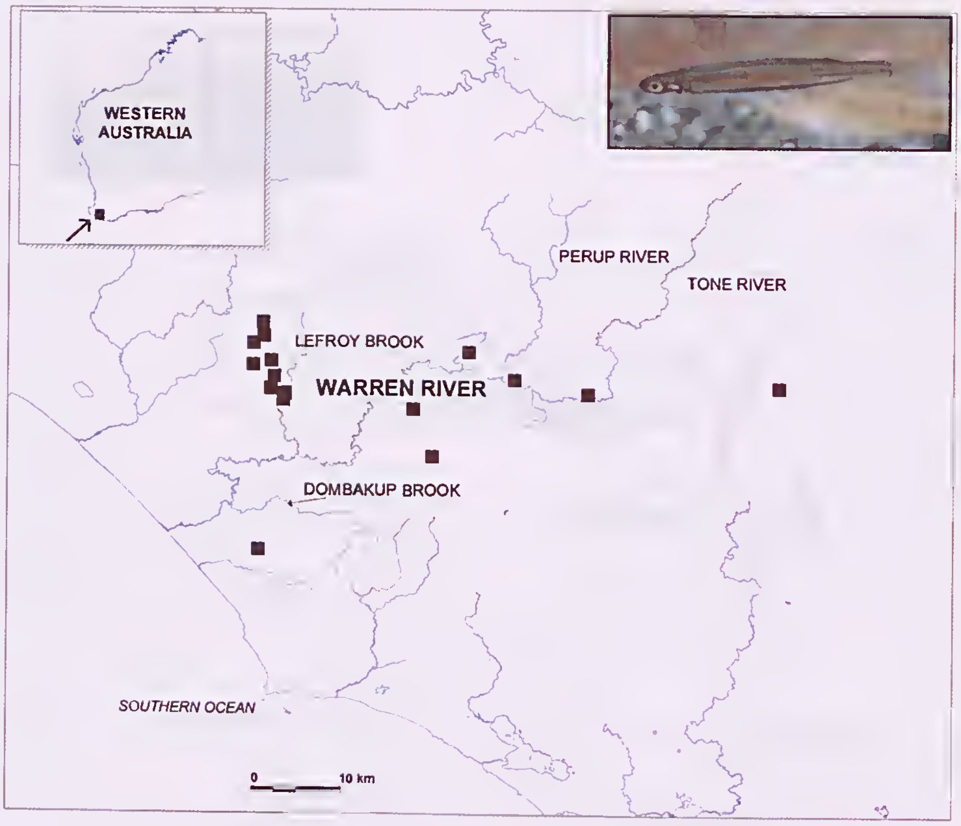


Figure 4. Distributions of the Black-stripe Minnow (top, photo G. Allen) and Mud Minnow (bottom, photo S. Beatty) in the Warren River catchment.

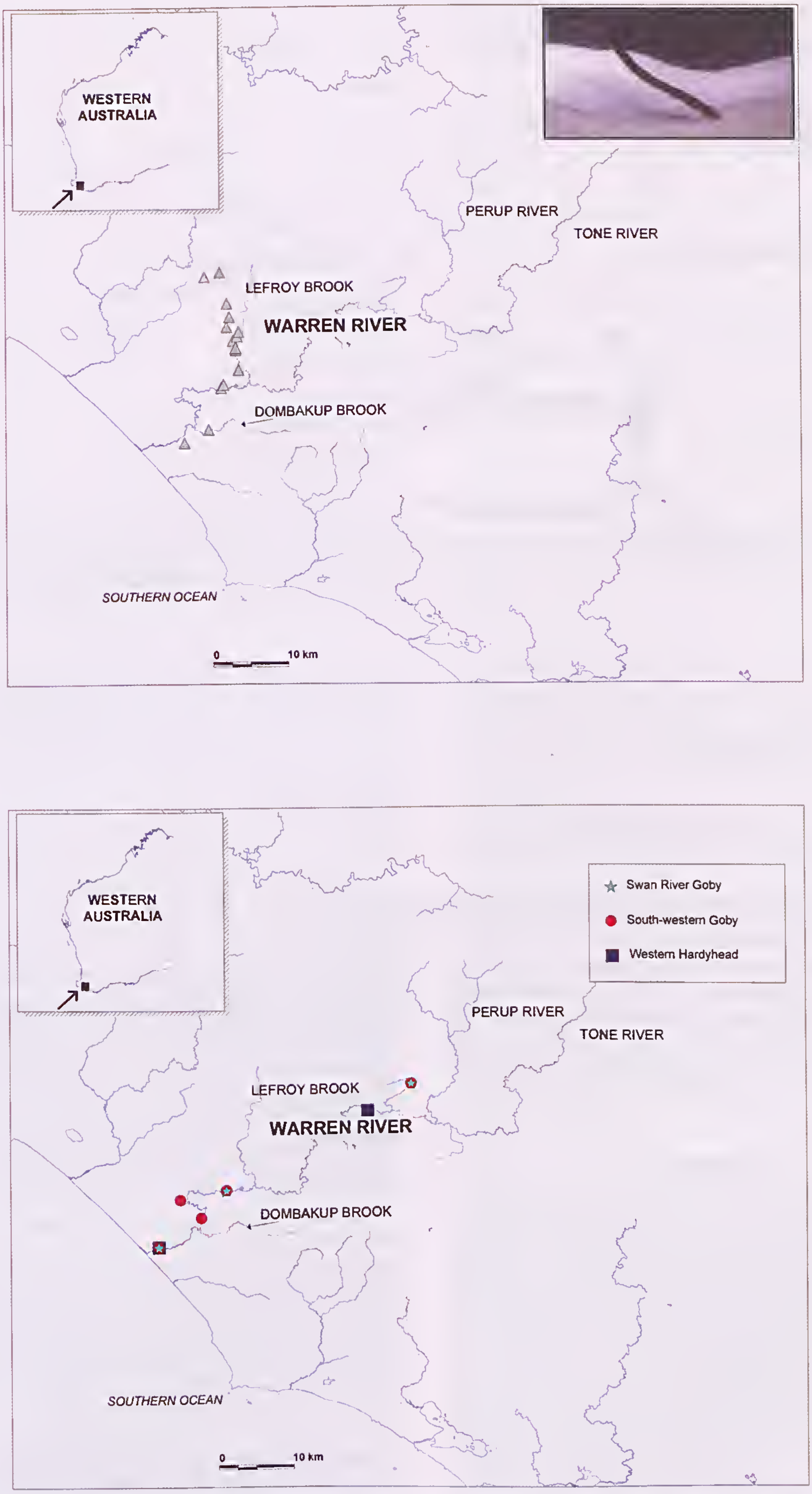


Figure 5. Distributions of the Pouched Lamprey (top, photo D Morgan) and estuarine fishes (bottom) in the Warren River catchment.

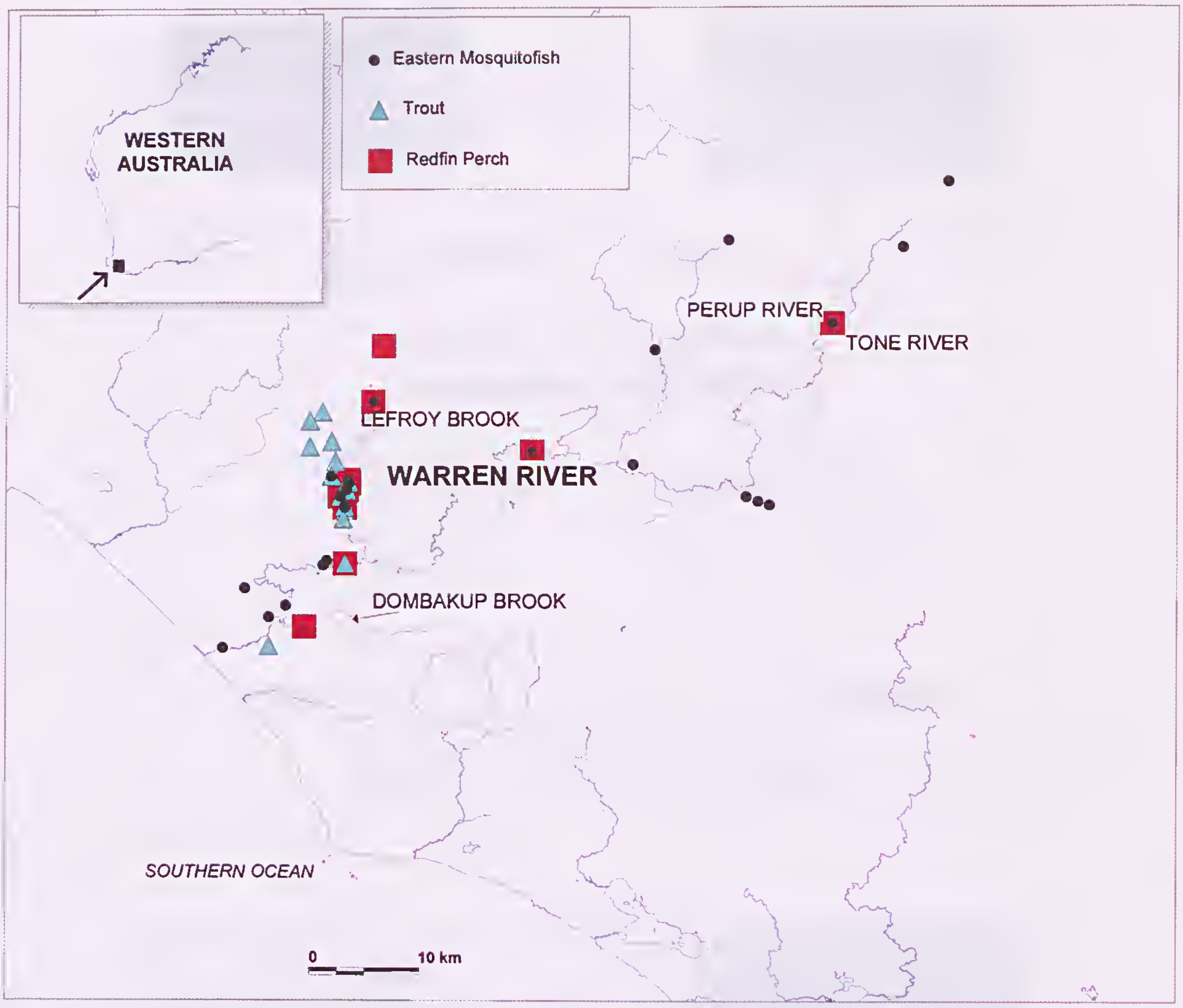


Figure 6. Historical distributions of the introduced fishes in the Warren River catchment.

suggests the taxa present in the main channel of the Warren River were generally tolerant of pollution (Table 1). However, a small increase in pollution sensitive taxa was detected moving downstream with the most upstream site (within cleared farmland) having the lowest composite and mean SIGNAL 2 scores (Table 1).

Discussion

Macroinvertebrates are commonly the key faunal group used as bioindicators to assess and monitor riverine health in south-western Australia (*e.g.*, Bunn & Davies 1992; Growns & Davis 1994; Smith *et al.* 1999; Armstrong *et al.* 2005). This is understandable given this group forms the basis of the predictive models in the widely used Australian River Assessment System (AusRivAS) that was derived from the British River Invertebrate Prediction and Classification System (RIVPACS, Wright *et al.* 1993), and also forms the basis for the SIGNAL 2 biotic index (Chessman 2003); employed in the current study. In south-western Australia, the AusRIVAS models were found to distinguish between undisturbed and severely disturbed sites but did not detect more subtle impacts (Smith *et al.* 1999). However, by examining multiple levels of ecosystems, biological integrity can be more comprehensively assessed (Simon 1999) with fish communities known to indicate direct and indirect stresses on aquatic ecosystems (Simon 1999). Therefore, incorporating both fish and macroinvertebrate community composition is often used in assessing and monitoring aquatic ecosystem health (*e.g.*, Harris 1995; Chessman 2003; Barton & Metzeling 2004; Hering *et al.* 2006; Solomon *et al.* 2006; Wang *et al.* 2007).

However, freshwater fish communities can be highly endemic and, compared to macroinvertebrates, relatively depauperate and therefore require an understanding of environmental tolerance and habitat requirements at the species level for them to be used as bioindicators. The freshwater fishes of south-western Australia are a prime example, as eight of the ten species are endemic; the highest rate of freshwater fish endemism of any drainage division in Australia (Allen *et al.* 2002).

Fishes of the Warren River and south-western Australia: potential as bioindicators

The Warren River was found to be an important system in terms of freshwater fish conservation; housing

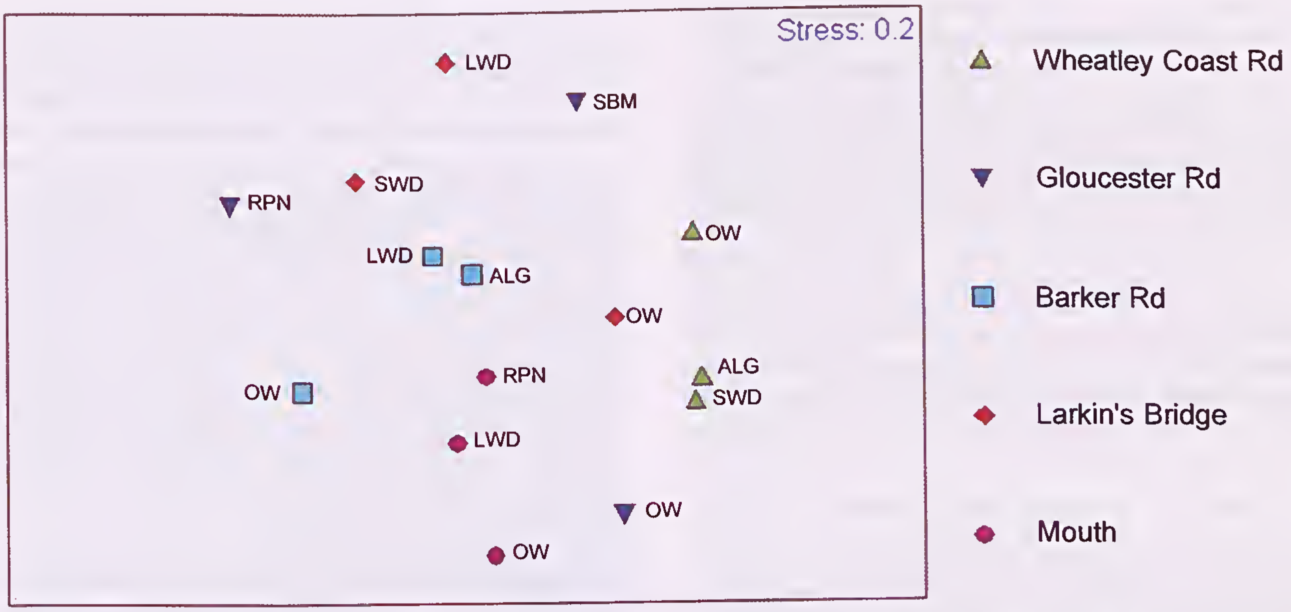


Figure 7. Ordination of the macroinvertebrate communities (using log abundances) at the sites sampled in the Warren River in December 2006. N.B. Habitat codes are: OW = open water, RPN = emergent riparian vegetation, SBM = submerged macrophytes, ALG = submerged macroalgae, SWD = small woody debris, LWD = large woody debris.

six of the eight endemic freshwater fishes of south-western Australia and is one of the important breeding and nursery grounds for the Pouched Lamprey. Sampling in the main channel of the river in the current study found that the reference sites housed four of these species *i.e.*, Western Minnow, Western Pygmy Perch, Nightfish and Freshwater Cobbler. This result is to be expected given that the other two species (*i.e.*, Black-stripe Minnow and Western Mud Minnow) are generally found in smaller tributaries or wetlands (Morgan *et al.* 1998). It is known that a number of the freshwater fishes of the South West Coast Drainage Division of Australia have been lost from inland reaches of major river systems and are now restricted to fresh habitats; particularly those that receive groundwater supplements during dry periods (Morgan *et al.* 1998, 2003; Beatty *et al.* 2006). However, specific gradual and acute salinity tolerances of these endemic species are currently unknown aside from the acute tolerances of the Western Minnow, Western Pygmy Perch and Balston's Pygmy Perch (Beatty *et al.* 2008). Nonetheless, as discussed below, a number of these species has the potential to be complementary to macroinvertebrate taxa in indicating ecological stress; particularly with regard to secondary salinisation.

Prior to this study, there were no documented reports of Freshwater Cobbler from the Warren River (Christensen 1982; Pen *et al.* 1988, 1991a, b; Jaensch 1992; Morgan *et al.* 1998, 2002). The species is usually only encountered within the main channel of river systems (Morgan *et al.* 1998; Beatty *et al.* 2006) and thus its absence from many of the previous studies that concentrated their sampling effort in the tributaries, is not unexpected. This species is thought to be tolerant of at least brackish or slightly saline conditions as it is restricted to the seasonally salinised lower main channel of the Blackwood River (Beatty *et al.* 2006), but is no longer found in the upper reaches of this or other major (many of which are salinised) rivers of the south-west such as the Blackwood River (Morgan *et al.* 2003; Beatty *et al.* 2006). This species, therefore, has the potential to be a useful bioindicator of salinisation in main channels of rivers of this region.

The Western Minnow is known to be relatively salt-tolerant with its acute salinity tolerance recently being recorded at ~14 ppt (Beatty *et al.* 2008); however, it has been recorded in salinities up to 24 ppt (Morgan & Beatty, unpublished data). This tolerance allows it to occupy secondarily salinised habitats where other non-salt tolerant natives have been excluded, as in the Blackwood River (Morgan *et al.* 2003). Therefore, its tolerance of moderate salinisation results in it potentially being a useful bioindicator of more severely salinised river reaches in this region. Its absence from the fresh habitat of Big Brook above Big Brook Dam in the Warren River is probably due to that structure (constructed in 1986) preventing its upstream spawning migration coupled with predation by introduced fishes (see below and Pen *et al.* 1988, 1991b; Morgan *et al.* 2002).

The Western Pygmy Perch has a similar acute salinity tolerance to the Western Minnow, *i.e.*, ~14 ppt (Beatty *et al.* 2008). However, along with the Nightfish, its inland range in south-western Australia has been greatly reduced and elevated salinity probably has other effects on both their life-cycles (*e.g.*, sperm viability, dietary requirements or low salinity tolerance of larvae) that prevent these two species occupying salinised systems. Therefore, both the Western Pygmy Perch and the Nightfish could be appropriate bioindicators of ecological impacts of salinisation in this region.

The less common Black-stripe Minnow is typically restricted to floodplain habitats that are better represented in adjacent catchments along the south-coast of south-western Australia (Morgan *et al.* 1998; Morgan & Beatty 2008). Based on its natural distribution (Morgan *et al.* 1998), it is unlikely that this species is tolerant of elevated salinities. Its specialised habitat requirement (*i.e.*, peat wetlands in the south-west corner of the South West Coast Drainage Division (Morgan *et al.* 1998)), however, renders it not being suitable as a bio-indicator of secondary salinisation within rivers of the south-west.

The Western Mud Minnow was once extremely common and widespread within the Big Brook catchment (see Pen *et al.* 1988, 1991a, b), however, a combination of the construction of the dam and the introduction of non-native fishes into this tributary have been implicated with the loss of this and other endemic fishes in this system (Morgan *et al.* 2002). As with the Black-stripe Minnow, it is unlikely that this species is tolerant of elevated salinities and its loss from the main channel of the Blackwood River has been attributed to secondary salinisation (Beatty *et al.* 2006; Phillips *et al.* 2007). Therefore, although other changes in habitats may impact the species, its absence from saline but otherwise suitable habitat within rivers in the South West Coast Drainage Division results in it potentially being a suitable bioindicator of secondarily salinised habitats.

The Warren River is arguably the most important breeding and nursery ground of the Pouched Lamprey in Western Australia and it contains those habitat types required to support larval (ammocoete) and metamorphosed (juvenile) lampreys, *i.e.*, well oxygenated sandy (for metamorphosed lampreys) and silty (for ammocoetes) substrates (Morgan *et al.* 1998). Therefore, as with the Western Mud Minnow, the Pouched Lamprey has certain microhabitat requirements, however, it is invariably found only in fresh habitats (Morgan & Beatty unpublished data). This species should, therefore, be considered an appropriate bioindicator of secondarily salinised habitats.

The three estuarine species recorded in the Warren River are essentially confined to the main channel and, as is the case with other salinised systems of south-western Australia, they may be relatively recent colonists of the inland reaches of the river (Morgan *et al.* 2003; Beatty *et al.* 2006). The extent of the upstream penetration of these estuarine species is highly likely to be a key bioindicator of ecological impact of salinisation of the region (Morgan *et al.* 2003; Beatty *et al.* 2006).

Introduced fishes of the Warren River

The Warren River is arguably one of the most popular areas for trout anglers in Western Australia and is annually stocked with hatchery reared fish by the Department of Fisheries, Western Australia (Department of Fisheries 2009). However, the degree of natural recruitment to the majority of these trout populations has not been assessed, nor has a detailed assessment of their ecological impact been undertaken in rivers of the south-west region. Interestingly, a recent study by Tay *et al.* (2007), who analysed both gut content and assimilated diet using stable isotope analysis, revealed the iconic Smooth Marron to be the most important (61% by overall volume) dietary component of Rainbow Trout in a water supply reservoir. Brown Trout have previously been recorded as self-sustaining in Big Brook Dam (Warren River catchment) (Morgan *et al.* 2004). Furthermore, self-sustaining populations of Rainbow Trout have recently been recorded in another reservoir (Tay *et al.* 2007) and stream (Morgan *et al.* 2008) in this region; therefore a cessation of the stocking regime alone may not result in the eradication of this species from the south-west.

Redfin Perch, an invasive species known to naturally reproduce in those systems it occupies (Morgan *et al.* 2002, 2004), was also widespread in the Warren River. Unlike the trout species, Redfin Perch has been the focus of a biological and impact study in Big Brook (including Big Brook Dam) (Morgan *et al.* 2002), the first of its kind for the species in Australia. The study recorded a localised loss of endemic fishes in Big Brook Dam that was attributed to its introduction to that system (Morgan *et al.* 2002). The species has an upper salinity tolerance of 10 ppt (Privolnev 1970) and therefore it can also potentially be used as an indicator of salinisation in those rivers in which it has colonised.

The Eastern Mosquitofish is another aggressive invasive species that is well known for fin-nipping native fishes (Gill *et al.* 1999). It is also very tolerant of saline conditions (up to at least ~58 ppt) being commonly found in the upper, cleared farmland reaches of river systems in the south-west and therefore although an indicator of degraded aquatic habitats in this region (see Morgan *et al.* 2003, 2004), is not a suitable indicator of salinisation.

The most upstream site (5) (Wheatley Coast Rd) had the highest movements (and captures) of the introduced Redfin Perch and Eastern Mosquitofish. This may indicate that this site was the most disturbed (as also suggested by the macroinvertebrate SIGNAL 2 index, see next section); however, it may also reflect the fact that these species are generally more prevalent in slower flowing environs (Morgan *et al.* 2002, 2004). Additional sampling of more upstream sites would determine whether these introduced species are more prevalent in more degraded habitats.

Aquatic invertebrates of the Warren River

The Smooth Marron was recorded in the main channel at four of the five reference sites sampled in the current study (being absent at the downstream-most site). This species is the third largest freshwater crayfish in the world, is fast growing, and is likely to be important in structuring food webs through consuming multiple levels of foodwebs (Beatty *et al.* 2005; Beatty 2006). The Warren River is a well recognised component of the recreational fishery for this species (Department of Fisheries 2008). Smooth Marron is known to be tolerant of slightly elevated salinities (lethal at ~17 ppt, Morrissy 1978). This species is an appropriate bioindicator for relatively large increases of salinity with its inland range in salinised rivers having been substantially reduced (Morrissy 1978).

Most of the invertebrate taxa recorded in the current study were consistent with those recorded by Trayler *et al.* (1996), who documented the different groups of aquatic fauna of the Warren River bioregion, including fish, frogs and invertebrates. Although noting that it was probably an underestimation (due to potential presence of undescribed species), the latter study found the region contained a relatively high proportion of the south-west endemic macroinvertebrate taxa and 17% of those found were locally endemic (Trayler *et al.* 1996).

The relatively low composite SIGNAL 2 scores at all sites suggest the macroinvertebrates present in the main channel of the Warren River are those generally tolerant of pollution. A steady increase in the salinity of the Warren River has already occurred during the past 50 years (Smith *et al.* 2006). As it is thought that the invertebrate fauna of the bioregion is intolerant of even small increases in salinity (Growns & Davis 1994; Trayler *et al.* 1996), it is likely that the macroinvertebrate communities have already been partially altered to consist of taxa that have a degree of salinity tolerance, or may have become adapted to environmental extremes and are now relatively insensitive to additional human disturbances such as land clearing or sediment loads (see Chessman *et al.* 2006). If the latter were the case, this would limit their usefulness as bioindicators in this system. However, a small increase in the pollution sensitive taxa was recorded at more downstream sites. This suggests that these communities may still be useful for monitoring current and future ecological impacts of water quality change (particularly salinisation) within the Warren River.

The slight increase in the SIGNAL 2 scores recorded here appears to contrast with Chessman (2003) who generally found lower scores further from the source of rivers, and higher scores at higher altitudes. This typical scenario may be the case in pristine upland areas in the Warren bioregion as relictual aquatic fauna are often found in elevated areas above previous zones of marine incursions (such as headwaters, granite outcrops, and permanent spring flows); as they provide moist, organic rich environments (Main & Main 1991; Trayler *et al.* 1996). Chessman (2003) also found that SIGNAL 2 scores were positively correlated with dissolved oxygen and negatively correlated with turbidity, conductivity (*i.e.*, salinity) and nutrients. Therefore, the subtle reverse SIGNAL 2 trend in terms of proximity to the source recorded in the current study may be due to the sites further downstream being in a more natural condition. This may be a result of them being located within the forested reserve system (*i.e.*, State Forest and/or National Park) and having lower salinities as a consequence of groundwater intrusion (Smith *et al.* 2006) compared with more upstream sites. A stronger pattern of decreasing SIGNAL 2 index may be revealed at sites even further upstream in the more saline farmland region. These base-line macroinvertebrate data suggest that on-going (and expanded) monitoring of the macroinvertebrate communities of the Warren River will provide a useful tool for assessing its long-term environmental condition.

Trayler *et al.* (1996) highlighted the importance of the reserve system in the Warren Bioregion stating that 25% of the region was held in National Parks or nature reserves (A-class) at that time; with 86% of the aquatic fauna being represented in reserves. The rivers and stream zone system (introduced in the 1970s and since modified), was stated as being of particular importance to these fauna as it was designed to provide buffer zones for water-ways against logging operations (Trayler *et al.* 1996). These buffer zones are important for preventing water quality decline in these systems as logging activities have been shown to reduce the macroinvertebrate richness. For example, clear-felling in Carey Brook (in the adjacent Donnelly River catchment) resulted in increased sediment loads and an associated decrease in the taxonomic richness and abundance of macroinvertebrates (Growns & Davis 1994).

The macroinvertebrate communities recorded in the current study represent an important ecological component that can be repeatedly monitored to assess ecological condition in the Warren River. It is recommended that additional sampling of fishes and macroinvertebrates occur at these sites and at more degraded upstream areas (*e.g.*, saline areas such as within the Tone River) during both spring and summer with both the SIGNAL 2 index and the AusRivAS assessment being applied to provide a more comprehensive base-line for long-term monitoring of the environmental condition of the river.

Conclusions

The current study has provided an assessment of two key bioindicator communities of the Warren River to allow future changes in its condition to be assessed; particularly in light of proposed management actions to address rising salinisation (see Smith *et al.* 2006). The study has identified a number of fishes as potentially appropriate bioindicators of salinisation of this and other rivers in the region. These species include the Freshwater Cobbler, Western Minnow, Western Pygmy Perch, Nightfish and the Western Mud Minnow. However the specific acute and gradual salinity tolerances of these species should be determined prior to their further incorporation in predictive ecological health models. The relatively low SIGNAL 2 scores at all sites suggested the macroinvertebrate taxa present in the main channel of the Warren River were generally tolerant of pollution, however, a small increase in the pollution sensitive taxa was recorded moving downstream with the upstream-most site having the lowest composite and mean SIGNAL 2 score. The use of multiple bioindicator groups should be more widely incorporated in assessing and monitoring riverine health in this region rather than relying on single levels of aquatic foodwebs as has commonly occurred in the past.

Acknowledgements: The authors gratefully acknowledgments funding support for the project from Southern Forests Landcare, Warren Catchments Council and South West Catchments Council. Particular thanks go to Lee Fontanini and Jenni Munroe for field and logistical support and Mahmoud Rashnavadi for laboratory assistance. Thanks to Howard Gill for reviewing drafts of the manuscript.

References

Allen G R, Midgley S H & Allen M 2002. Field Guide to the Freshwater Fishes of Australia. Western Australian Museum, Perth.

Armstrong K N, Storey A W & Davies P M 2005 Effects of catchment clearing and sedimentation on macroinvertebrate communities of cobble habitat in freshwater streams of southwestern Australia. Journal of the Royal Society of Western Australia 88: –11.

Barton J L & Metzeling L 2004 The development of biological objectives for streams in a single catchment: a case study on the catchment of Western-Port Bay, Victoria, Australia. Environmental Monitoring & Assessment 95: 39–256.

Beatty S J, Morgan D L & Gill H S 2005 Biology of a translocated population of the large freshwater crayfish, *Cherax cainii* (Austin & Ryan, 2002) in a Western Australian river. Crustaceana 77(11): 1329–1351.

Beatty S J 2006 The diet and trophic positions of translocated, sympatric populations of *Cherax destructor* and *Cherax cainii* in the Hutt River, Western Australia: evidence of resource overlap. Marine & Freshwater Research 57(8): 825–835.

Beatty S & Morgan D 2006 Management of aquatic fauna during refurbishment of Phillips Creek Reservoir. Murdoch University, Centre for Fish & Fisheries Research report to the Water Corporation of Western Australia.

Beatty S J, Morgan D L, McAleer F J, Koenders A & Horwitz P H J 2006 Fish and crayfish communities of the Blackwood River: migrations, ecology, and influence of surface and groundwater. Report to the South-west Catchments Council and Department of Water.

Beatty S, Rashnavidi M, Morgan, D & Lymbery A 2008 Salinity tolerances of native freshwater fishes of the Blackwood River. Centre for Fish & Fisheries Research, Murdoch University. Report to South West Catchments Council.

Boulton A J, Marmonier P & Sarriquet P E X 2007 Hyporheic invertebrate community composition in streams of varying salinity in southwestern Australia: Diversity peaks at intermediate thresholds. River Research &Applications 23(6): 79–594.

Bunn S E & Davies P M 1992 Community structure of the macroinvertebrate fauna and water-quality of a saline river system in south-western Australia. Hydrobiologia 248(2): 43–160.

Chessman B C 2003 New sensitivity grades for Australian river macroinvertebrates. Marine & Freshwater Research 54: 5–103.

Chessman B C, Thurtell L A & Royal M J 2006 Bioassessment in a harsh environment: a comparison of macroinvertebrate assemblages at reference and assessment sites in an Australian inland river system. Environmental Monitoring & Assessment 119: 303–330.

Christensen P 1982 The distribution of *Lepidogalaxias salamandroides* and other small fresh-water fishes in the lower south-west of Western Australia. Journal of the Royal Society of Western Australia 65: 131–141.

Clarke K R & Gorley R N 2001 Primer v5: User manual/tutorial. PRIMER-E Ltd: Plymouth, United Kingdom.

Collins P D K & Barrett D F 1980 Shannon, Warren and Donnelly River Basins – water resources survey. Western Australia Public Works Department, Water Resources Branch, Report No. WRB 6, 24 p.

Crandall K A, Fetzner J W, Lawler S H, Kinnersley M, & Austin C M 1999 Phylogenetic relationships among the Australian and New Zealand genera of freshwater crayfishes (Decapoda: Parastacidae). Australian Journal of Zoology 47: 199–214.

Davis J A, McGuire M, Halse S A, Hamilton D, Horwitz P, McComb A J, Froend R H, Lyons M & Sim L 2003 What happens when you add salt: predicting impacts of secondary salinisation on shallow aquatic ecosytems by using an alternative-states model. Australian Journal of Botany 51(6): 715–724.

Department of Fisheries 2009 A five-year management strategy for the recreational trout fishery. Fisheries Management Paper No. 234. Department of Fisheries, Government of Western Australia. Perth, Western Australia.

Department of Fisheries 2008 State of the Fisheries Report 2007/08. (W J Fletcher & K Santoro eds). Department of Fisheries, Government of Western Australia, Perth, Western Australia.

Fausch K D, Lyons J, Karr J R, Angermeier P L 1990 Fish communities as indicators of environmental degradation. *In*: American Fisheries Society Symposium, 8. Biological indicators of stress in fish (ed M Adams). American Fisheries Society: Bethesda, Maryland, USA.

Gill H S, Hambleton S J, & Morgan D L 1999 Is *Gambusia holbrooki* a major threat to the native freshwater fishes of south-western Australia? *In*: Proceedings 5th Indo-Pacific Fish Conference (Noumea, 3–8 November 1997), (eds B Seret & J Y SireY). Paris: Societe Francaise d'Ichtyologie & Institut de Recherche pour le Development. pp. 79–87.

Growns I O & Davis J A 1994 Effects of forestry activities (clearfelling) on stream macroinvertebrate fauna in south-western Australia. Australian Journal of Marine and Freshwater Research 45: 963–975.

Harris J H 1995 The use of fish in ecological assessments. Australian Journal of Ecology 20(1): 65–80.

Higgins C L & Wilde G R 2005 The role of salinity in structuring fish assemblages in a prairie stream system. Hydrobiologia 549: 197–203.

Hering D, Johnson R K, Kramm S, Schmutz S, Szoszkiewicz K & Verndonschot P F M 2006 Assessment of European streams with diatoms, macrophytes, macroinvertebrates and fish: a comparative metric-based analysis of organism response to stress. Freshwater Biology 51(9): 1757–1785.

Hoagstrom C W 2009 Causes and impacts of salinization in the lower Pecos River, Great Plains Research 19(1): 1052–5165.

Hodgkin E P & Clarke R 1989 Estuaries and coastal lagoons of south western Australia. Broke Inlet and other estuaries of the Shire of Manjimup. Estuarine Studies Series Number 6. Environmental Protection Authority, Perth, Western Australia.

Jaensch R P 1992 Fishes in wetlands on the south coast of Western Australia. Unpublished Technical Paper. Department of Conservation and Land Management, Perth, Western Australia.

Karr J & Dudley D 1981 Ecological perspectives on water quality goals. Environmental Management 5: 55–68.

Main A R & Main B Y 1991 Report on the Southern Forest Region of Western Australia. Report for the Australian Heritage Commission, Perth.

Mayer X, Ruprecht J, & Bari M. 2005 Stream salinity status and trends in south-west Western Australia. Department of Environment Salinity and Land Use Impact Series, Report No. SLUI 38.

Morgan D L & Beatty S J 2008 The Donnelly River catchment: an important refuge for all of south-western Australia's endemic freshwater fishes and the Pouched Lamprey (*Geotria australis*). Journal of the Royal Society of Western Australia 26: 112–127.

Morgan D L, Gill H S & Potter I C 1998 Distribution, identification and biology of freshwater fishes in south-western Australia. Records of the Western Australian Museum Supplement No. 56, 97 pp.

Morgan D L, Gill H S & Potter I C 2000 Age composition, growth and reproductive biology of the salamanderfish *Lepidogalaxias salamandroides*: a re-examination. Environmental Biology of Fishes 57: 191–204.

Morgan D L, Hambleton S J, Gill H S & Beatty S J 2002 Distribution, biology and likely impacts of the introduced redfin perch (*Perca fluviatilis*) (Percidae) in Western Australia. Marine & Freshwater Research 53: 1211–1221.

Morgan D L, Thorburn D C & Gill H S 2003 Salinization of south-western Western Australian rivers and the implications for the inland fish fauna – the Blackwood River, a case study. Pacific Conservation Biology 9: 161–171.

Morgan D L, Gill H S, Maddern M G & Beatty S J 2004 Distribution and impacts of introduced freshwater fishes in Western Australia. New Zealand Journal of Marine and Freshwater Research 38: 511–523.

Morgan D L, Beatty S J, McAleer & Fazeldean T 2008 Survey of Rainbow Trout in Bancell Brook: following the cessation of a stocking programme. Technical Report to the Peel-Harvey Catchment Council. Centre for Fish and Fisheries Research, Murdoch University, Perth, Western Australia.

Morrissy N M 1978 The past and present distribution of marron, *Cherax tenuimanus*, in Western Australia. Fisheries Research Bulletin of Western Australia 22: 1–38.

Nielsen D L, Brock M A, Rees G N & Baldwin D S 2003 Effects of increasing salinity on freshwater ecosystems in Australia. Australian Journal of Botany 51(6): 655–665

Pen L 1997 A systematic overview of environmental values of the wetlands, rivers and estuaries of the Busselton-Walpole region. Water Resource Allocation and Planning Report Series Report No. 7.

Pen L J, Hilliard R W, & Potter I C 1988 The effect of Big Brook dam and the Pemberton Weir on the migration of native fish. Report to the Western Australian Water Authority, Perth, Western Australia.

Pen L J, Potter I C, & Hilliard R W 1991a Biology of *Galaxiella munda* McDowall (Teleostei: Galaxiidae), including a comparison of the reproductive strategies of this and three other local species. Journal of Fish Biology 39: 717–31.

Pen L J, Potter I C, & Power G W 1991b Fish and lamprey monitoring in the Lefroy/Big Brook system in south-western Western Australia. Report to the Western Australian Water Authority, Perth, Western Australia.

Phillips N, Chaplin J, Morgan D & Beatty S 2007 The evolutionary significance of Balston's Pygmy Perch and Mud Minnow populations in the Blackwood River. Centre for Fish & Fisheries Research (Murdoch University). Report to Department of Water.

Privolnev T I 1970 Reaction of freshwater anadromous and catadromous fish to varying salinity. *In*: Fish physiology in acclimatisation and breeding (ed T I Privolnev). Israel Program of Science Translation, Jerusalem, Israel.

Simon T P 1999 Introduction: Biological integrity and use of ecological health concepts for application to water resource characterisation. *In*: Assessing the sustainability and biological integrity of water resources using fish communities (ed T P Simon). C.R.C. Press.

Smith M G, Dixon R N M, Boniecka L H, Berti M L, Sparks T, Bari M A & Platt J 2006 Salinity situation statement: Warren River. Western Australian Department of Water, Water Resource Technical Series No. WRT 32.

Smith M J, Kay W R, Edward D H D, Papas P J, Richardson K St J, Simpson J C, Pinder A M, Cale D J, Horwitz P H J, Davis J A & Yung F H 1999 AusRivAS: using macroinvertebrates to assess ecological condition of rivers in Western Australia Freshwater Biology 41: 269–282

Solomon J J, Brodie R B & Ehlinger G S 2006 Distribution and abundance of fish assemblages and select macroinvertebrates from the Lower St. Marys River Basin in northeast Florida. Florida Scientist 69: 1–18.

Tay M Y, Lymbery A J, Beatty S J & Morgan D L 2007 Predation by Rainbow Trout (*Oncorhynchus mykiss*) on a Western Australian icon: Marron (*Cherax cainii*). New Zealand Journal of Marine & Freshwater Research 41: 197–204.

Trayler K M, Davis J A, Horwitz P & Morgan D 1996 Aquatic fauna of the Warren bioregion, south-west Western Australia: Does reservation guarantee preservation? Journal of the Royal Society of Western Australia 79: 281–291.

Wang L Z, Robertson D M & Garrison P J 2007 Linkages between nutrients and assemblages of macroinvertebrates and fish in wadeable streams: Implications to nutrient criteria development. Environmental Management 39(2): 194–212.

Wright J F, Furse M T & Armitage P D 1993 RIVPACS – a technique for evaluating the biological quality of rivers in the UK. European Water Pollution Control 3(4): 15–25.

Journal of the Royal Society of Western Australia, 93: 81–113, 2010

Coastal geoheritage: a hierarchical approach to classifying coastal types as a basis for identifying geodiversity and sites of significance in Western Australia

M Brocx[1] & V Semeniuk[2]

[1] Division of Science & Engineering
Murdoch University, South St., Murdoch, WA, 6150
[2] V & C Semeniuk Research Group
21 Glenmere Rd., Warwick, WA, 6024

Manuscript received September 2009; accepted February 2010

Abstract

Identifying sites of coastal geoheritage significance begins with classification of coastal geology and geomorphology. However, classifying coasts for purposes of geoheritage is made difficult due to the complexity, intergradation, and different scales at which coastal features are expressed, with variation potentially present locally or regionally. Also, geoheritage must address geological content as well as coastal geomorphology expressed erosionally and/or sedimentologically, and Earth history as manifested in coastal erosional and stratigraphic products. While geological and environmental settings play important roles in determining regional variation in coastal form and coastal products, or expression of geological content, coasts at the local scale commonly are expressions of one or more of the main processes of (marine) inundation, erosion, and deposition, and/or of subdominant processes of biogenic activity and diagenesis. To address this coastal geodiversity for geoheritage and geoconservation in Western Australia, a three-level scalar hierarchical approach is used. Level 1 identifies the regional geological and environmental setting, *i.e.*, recognising major cratons and basins, and the climatic/oceanographic setting of a coast, which determine regional coastal forms. Level 2 identifies the main coastal types developed by coast-forming processes (*e.g.*, marine inundation of pre-existing landforms; coastal erosion; exhuming of older landforms; construction by Holocene sedimentation, coasts formed biogenically, amongst others), as well as coastal types that illustrate Holocene history geomorphically or stratigraphically, or manifest pre-Holocene rock sequences in sea cliffs. Level 3 identifies finer-scale characteristics particular to any coast within its regional setting to develop an inventory of features providing data within the context of the coastal types for comparative geoconservation purposes. All three levels need to be applied to fully categorise coasts for assessing geoheritage values and for geoconservation.

Keywords: coastal geoheritage, coastal types, geoheritage, geoconservation, geodiversity, coastal classification, hierarchical coastal classification.

Introduction

As the zone of intersection and interaction of land, sea, groundwater, and atmosphere, and the processes therein, the coast is one of the most complex environments on the Earth's surface, with a multiplicity of processes operating at a number of scales. With other matters such as lithology, structure, or geological framework being equal, the coastal zone generally results in greater geodiversity in processes and products than elsewhere (Brocx & Semeniuk 2009). As such, it is an environment where there should be a focus on geoconservation and to date, indeed, there have been many coastal locations of geoheritage significance identified at the global and national level (particularly rocky shores and cliffs with their exposures illustrating geological history, types sections, or geological principles). However, the coastal zone is one of the most difficult environments to classify into natural groups, for a number of reasons: 1. it is complex, spanning geology, geomorphology, biogenesis[1] and diagenesis; 2. there are features that are specifically formed at the coast that are not part of natural gradations or groupings (*e.g.*, diagenetic products); 3. good exposures of geological sequences of geoheritage significance in natural cliffs are *ad hoc* products of coastal erosion and not part of a coastal gradation or coastal system; and 4. there are various scales at which geological features are evident. This complexity has not been previously recognised in assigning geoheritage significance and undertaking geoconservation.

---

[1] *Biogenesis* has two meanings: in Geology it refers to the formation by organisms of products such as coral reefs, shells, or bioturbation structures (*i.e.*, formed biogenically), while in Biology it refers to the principle that organisms arise only by the reproduction of other organisms (Bates & Jackson 1987). The term is used more commonly in the realm of Biology. In this paper, we use *biogenesis* in the geological sense, but also *biogenic activity* and *biogenic process(es)* as more general process-oriented terms.

Coasts have been classified previously from a number of scientific perspectives and purposes and at different specific scales, and using a variety of approaches, and such classifications have resulted in an understanding of coastal forms or coastal evolution at global scale down to local scale, in models of sedimentation and stratigraphy oriented towards geohistory and/or resource exploration, in developing a framework for habitats, and in rational environmental management of the coastal zone. As such, there is a large body of literature dealing with categorisation of coastal forms based on their morphology, origin, evolution, and tectonic, oceanographic, or climatic setting (Johnson 1919; Valentin 1952; Bloom 1965; King 1972; Shepard 1973; Davies 1980; Kelletat 1995; Woodroffe 2002; Schwartz 2005). However, the various classifications developed to date have not lent themselves to be directly applicable to issues of geoheritage and geoconservation. For instance, genetic classifications provide an understanding of coastal evolution, coastal development, or coastal types but have not been useful in comparative studies for geoheritage and geoconservation in that they tend to be process-oriented.

Thus, while coastal classification systems abound, coasts have not been systematically classified for the purposes of recognising sites of geoheritage significance and for geoconservation. Moreover, geoheritage and geoconservation are relatively young endeavours compared to other established disciplines involved with the coast. For example, sedimentology is a long-established science (Wentworth 1922; Krumbein & Pettijohn 1938; Twenhofel 1939; Shrock 1948; Pettijohn 1949; Allen 1970), and sedimentologists have developed coastal classifications at regional scale (*e.g.* delta forms, barrier islands, amongst others), and an understanding of sedimentary sequences and sedimentary products at finer scales (Reineck & Singh 1980). Similarly, coastal geomorphologists have classified coasts (though occasionally somewhat differently to sedimentologists) generally at regional to large scales and, at a more detailed scale, rocky shore specialists, for example, have classified medium and small-scale erosional features along coasts. All such classifications have been directed to the objective of the specialist science and (axiomatically) not in a manner to provide information directly to identify sites of geoheritage significance or for geoconservation, though their information is useful for comparative geoheritage and geoconservation usually at small scales of reference. Locally, where researchers have attempted to address geoheritage of coastal zones, they have applied existing terms and established classification(s) of smaller-scale geomorphic and sedimentological features. This has resulted in an inventory of coastal features (*e.g.*, Kiernan 1997) rather than a coastal classification for geoheritage purposes.

Whether it is species, ecosystems, or physical features, it is the differences (or diversity) in types of natural features, *viz.*, biodiversity or geodiversity, as well as their rarity and representativeness that form the basis of selection of species, or of sites for conservation. Identification of coastal types, *i.e.*, the "species of coasts", and their geodiversity, should form the prelude to identifying sites of geoheritage significance. To this objective, this paper presents a classification of coastal types as the first step in identifying sites of geoheritage significance for geoconservation and coastal management. We present here a hierarchical approach that identifies, in the first instance, "families" of coastal types, as a context and a prelude to identifying "species of coasts".

Coasts initially can be categorised according to geological setting, (*e.g.*, Precambrian rock coast, Tertiary limestone coast, Quaternary limestone coast), climatic setting (*e.g.*, tropical; humid or tropical arid coasts), and oceanographic setting. Thereafter, coasts can be separated on the basis of forms developed by marine inundation, erosion, sedimentation, biogenesis, or diagenesis (as will be described later) and then, if necessary, subdivided into finer scales that result in recognition of further forms and patterns. There can be variation along the coast in terms of processes and products and development of coastal types, and these can be present at different scales within a region, and across regions. Also, many coastal localities around the world have classic exposures of types sections, reference sections, fossil occurrences, geological features such as large nodules and columnar jointing, and exposures illustrating Earth history (exposing geohistorical sequences). As a zone of interaction of sea, land, atmosphere and groundwater, it can also be a zone of distinct diagenesis. In this paper, categories of coastal features or coastal types are classified in order to identify sites that may have geoheritage significance within a context of geological region and environmental setting (climate/oceanography). This approach to assessing sites of geoheritage significance will be developed further in future papers.

The coastline of Western Australia provides an excellent starting point for the development of a coastal classification for purposes of geoheritage and geoconservation as it manifests a wide variety of coastal forms along its 8000 km length and 22° of latitudinal range, a length that transcends several geological regions (*viz.*, the Kimberley region, the Canning Coast, through to the Eucla Basin), several climate zones (from tropical to near-temperate, and humid to arid), and various oceanographic and coastal settings (from macrotidal to microtidal, from wave-dominated to tide-dominated, from protected to wind-dominated).

In contrast, European countries, while trans-nationally complex, tend to involve only short segments of the subcontinental geological, climatic, and oceanographic variability as represented in Western Australia. A further contrast is provided by the western coast of the Americas, being a collision coast, while transcending a large latitudinal distance and climate belts, presents at the megascale a relatively uniform coastal form of uplift determined by tectonic plate collision.

Terms, scope and scale, involved in coastal geoheritage

The term *coast* is used to denote the modern environment separating land and sea, and generally occurring between high and low tide, and the term *coastal* is used to denote a variety of environments that are related to the interaction between oceanic and terrestrial processes (Brocx & Semeniuk 2009). As such, coastal zones will contain both land and ocean components, and have boundaries to the land and ocean that are determined by the degree of influence of the land on the ocean and the ocean on the land; and may not be of uniform width, height, or depth (Kay & Alder 1999). These environments may include the seaward margin of prograded coastal plains, or coastal dune belts (where they have been formed by coastal processes), or areas influenced by marine processes such as salt spray.

In this context, the term *coastal geoheritage* is used to denote geoheritage aspects of the coastal zone where the coastal zone is the shore, and where terrestrial and oceanic areas are, or have been, influenced by Holocene coastal processes.

Since coasts are Holocene, the emphasis on coastal geoheritage features is on Holocene forms, whether they are marine inundation features (formed by the last post-glacial transgression), erosional features cut into materials of Holocene, Pleistocene, or older age, or depositional landforms and sedimentary sequences developed during the Holocene. As such, Pleistocene coastal landforms, Pleistocene coastal sedimentary sequences, and other Pleistocene features (regardless of how closely they spatially are related to Holocene shorelines), and exhumed pre-Holocene former coastlines (such as exhumed cliffs or rocky shore pavements), are relegated to the category of ancient sequences. Stranded sea cliffs of Pleistocene age or earlier, are not included in this definition of coast or coastal.

The term *bedrock* is used in this paper to refer to rocks of sedimentary, igneous, and metamorphic origin, of Precambrian to Phanerozoic age (*e.g.*, the Silurian Tumblagooda Sandstone, and the Mesozoic Broome Sandstone), and not only to Precambrian basement rocks.

Following Brocx & Semeniuk (2007), the scope of geoheritage involves different categories of sites, all of which can be identified in the coastal zone.

- type examples, reference sites or locations for stratigraphy, fossils, soil reference profiles, mineral sites, and geomorphic sites, including locations for teaching research, and reference;
- cultural sites where classic locations have been described;
- geohistorical sites where there are classic exposures in cliff and outcrops where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed;
- modern, active landscapes where dynamic processes are operating.

Cliffs, or other types of coastal outcrops, that expose ancient sequences (ranging from Precambrian in age such as the sequences exposed in cliffs along the central Pilbara Coast, to cliffs exposing Mesozoic or Cainozoic sequences such as along the edge of the Sydney Basin in New South Wales, or the edge of the Nullarbor Plain, respectively, to cliffs of Quaternary limestones as exposed at Zuytdorp Cliffs, Western Australia) clearly represent the category of geohistorical sites in which there are exposures from which the history of the Earth or the processes within the Earth in the past can be reconstructed.

For the category of "modern, active landscapes", Sharples (1995) expanded the original idea of geoheritage to include areas of dynamic geological processes which could include environments such as mobile coastal dunes, or fluvial systems with annual or episodic floods. This notion is explored further here, as it is relevant to assigning coastal types to categories of modern, active landscapes, or to geohistorical sites. These two categories, in fact, can grade into each other.

Landscapes can gradationally vary from being very active (*e.g.*, mobile inland-ingressing parabolic dunes), to episodically active (*e.g.*, floods in riverine systems in arid zones), to largely now inactive, but intermittently active over the Holocene (*e.g.*, arid zone fluvial systems, or prograded coastal plains). Further, where there is a combination of active geomorphic, sedimentological and diagenetic processes operating in an area, one of the processes may be episodic, another intermittent, and the third ongoing, and each may have different rates and intensities when active, and various expressions in a gradient normal to the coast. For separating geohistorical sites from active modern landscapes, this temporal and spatial gradation in landscape activity and dynamism is further discussed in terms of what constitutes "dynamic process", and how far inland should the idea of "dynamic process" for coasts be taken.

The majority of coastal scientists would agree that mobile, landward-ingressing, coastal parabolic dunes accord with the notion of "dynamic". Similarly, relatively rapidly accreting coasts, such as the Gascoyne Delta (Johnson 1982) and Point Becher (Searle *et al.* 1988), or eroding coasts, retreating at, say, 1 m per annum, as recorded in cliffs cut into mud in King Sound (Semeniuk 1981a), along the sandy seafront of the Leschenault Peninsula (Semeniuk & Meagher 1981), and the retreating cliff along the edge of the Nullarbor Plain, with its continual development and erosion of shoreline talus (breccia and megabreccia) deposits, would also constitute dynamic environments where processes are extant. Slow retreat of limestone rocky shores, measured in rates of < 1 mm per annum (Hodgkin 1964), under the action of algae-grazing molluscs, other forms of bioerosion, wave abrasion, or chemical corrosion also could be considered as dynamic, albeit at reduced rates. In these latter examples, the coast is still actively eroding, but not so conspicuously. This poses the question of how rapid a process must be for it to be designated as "dynamic". For instance, for erosional coasts, various studies on different materials and rock types under different processes show varying rates of erosion (Hodgkin 1964; Gill 1973; Semeniuk & Meagher 1981; Semeniuk 1981a, May & Heeps 1985) and, conversely, for prograding coasts, there are varied rates of accretion (for deltas, cuspate forelands, and arid coastal sedimentation, see Fisk 1961, Searle *et al.* 1988, Semeniuk 1996a and Semeniuk 2008, respectively). In this paper, all extant processes at the coast are classed as dynamic, regardless of whether they are rapid and visually conspicuous, or extremely slow, but nonetheless effecting change in landforms through agencies of erosion or sedimentation, or where they result in diagenetic products. That is, it is Holocene coastal processes *in action* that constitute a dynamic environment, or it is where processes still contribute to an ongoing developing system.

Coastal processes can change in style, effect, and intensity, spatially and temporally. Spatially, they may be conspicuous and marked at the coast, and change inland because there is a gradient in hydrochemistry, or because of decreasing intensity (*e.g.*, decrease in seabreeze velocity), or change in processes (*e.g.*, marine water diagenesis giving way to fresh-water diagenesis). Dunes ingressing inland under the effect of coastal winds may be subject to marine/brackish water diagenesis at the coast and freshwater diagenesis in inland locations.

For modern, active (coastal) landscapes, the main ubiquitous processes include sedimentation, erosion, biogenic processes, and diagenesis, and these processes may be continually operating, or intermittently operating, or have the potential to be reactivated. In the case of prograding coasts, generally the most dynamic portion of the landscape is the seaward part or the seaward edge of a prograded/prograding plain, with a stranding of the earlier deposits inland, and a consequent decrease in activity of coastal processes towards inland. The attendant effect is that processes of sedimentation and erosion may/will progressively decrease inland. Three coastal landscapes and their processes are described below to demonstrate the extent that active processes may extend inland: a prograding tidal flat, a prograding beach-ridge plain, and coastal barrier dunes.

In the case of prograding tidal flats, the main processes are sedimentation, biogenic activity, and diagenesis. The seaward parts of tidal flats involve accumulation/accretion and biogenic activity on the low intertidal to high intertidal flats, with development of stranded flats that are inundated only on the highest (equinoctial tides) and by storm waters. But for such environments, while there will be annual inundation by the highest tides and storm water, these tidal flats also are subjected to on-going coastal hydrochemical, groundwater, and other processes (that are graded from the level of the low tidal level to that of the highest tide) that diagenetically imprint on the stranded flats (Logan 1974; Semeniuk 1981a, 1981b, 2008). In the case of prograding beach-ridge plains, the main processes are sedimentation, intermittent erosion, and diagenesis. With progradation, the beach surface shoals become incipient beach ridges, and beach ridges become emergent above the level of the highest tides and storms by vertical aeolian accretion of sand ridges (Searle *et al.* 1988; Semeniuk *et al.* 1989; C A Semeniuk 2007). Thus, in contrast to tidal flat systems, there is a decrease to some extent in coastal effects in regard to sedimentation and accumulation in stranded parts of such systems. However, with beach-ridge plains the coastal zone may later be subjected to coastal wind erosion and sand remobilisation (forming inland-transgressing parabolic dunes), originating from the coast zone itself, and still is within the realm of active coastal processes though this may be staggered in time and space. In this case, the entire package of seaward-edge processes of sedimentation and any concurrent mobilisation of dunes towards inland, the reactivation of inland ingressing dunes, wind erosion of stranded beach ridges and dunes are all part of the ensemble of "modern, active landscapes where dynamic processes are operating", as distinct from terrains of Quaternary limestone, or older rock sequences that have not been actively formed as part of the modern landscape. Similarly, any diagenesis effected on the beach-ridge plain is part of the same ensemble of "modern, active landscapes where dynamic processes are operating". The same principles apply to coastal barrier dunes. The most active zone is the seaward edge *and* the coastal zone immediate to the shore. However, for coastal barrier dunes, the coastal zone may later be subjected to wind erosion and sand remobilisation, forming inland-transgressing parabolic dunes, and still is within the realm of active coastal processes which may be staggered in time and space (Semeniuk & Meagher 1981).

For the examples presented above, prograded tidal flat and beach-ridge plains, as well as coastal barrier dunes, are considered to be modern landscapes with dynamic processes, and the plains in particular are the result of active edge-of-sea sedimentation. In older parts of such systems, modern diagenesis and reactivation of dunes still place these environments within the category of active and extant. However, on the oldest parts of such systems, the landscapes may change from being modern and active to geohistorical sites where there are exposures in cliffs and outcrops recording the history of the Earth, or the past processes within the Earth.

Scale should be a factor considered, even as a descriptor, in developing classification of sites for purposes of geoheritage and geoconservation, because significant features can be terrane size or crystal size, and both may be present in the same area (Brocx & Semeniuk 2007), and similar coastal features may be present at different scales (Semeniuk 1986). In the coastal zone, features can range from large systems such as deltas, to specific types of cliffs, to micro-pinnacles (= "lapiés" *cf.* Paskoff 2005) and tafoni. Most literature on coastal classification or on coastal evolution tends to deal with phenomena at one frame of reference and do not transcend scale. Scale is formally addressed in this paper in terms of frames of fixed sizes, using regional, large, medium, small, and fine scales (Semeniuk 1986), or megascale, macroscale, mesoscale, microscale, and leptoscale (C A Semeniuk 1987). Cross-lamination, sedimentary layering, bubble sand, shell layers, and tafoni, for instance, are evident within a 1 m x 1 m frame of reference, while cliff faces, shoreline benches and sandy spits are evident within a 10 m x 10 m to 100 m x 100 m frame of reference. Scales of reference for geomorphic/geoheritage features in this paper, for use as descriptors, are: regional scale (or megascale) within a frame 100 km x 100 km or larger; large scale (or macroscale) within a frame 10 km x 10 km; medium scale (or mesoscale) within a frame 1 km x 1 km; small scale (or microscale) within a frame 10–100 m x 10–100 m; and fine scale (or leptoscale) within a frame 1 m x 1 m, or smaller.

Global coastal classifications – and their potential applicability to geoconservation

There have been a number of classifications published for coastal systems, as summarised by King (1972), Schwartz (1982), Kelletat (1995), Fairbridge (2004), and Finkl (2004). They grade from over-arching and conceptual (*e.g.*, Johnson 1919, Valentin 1952, Bloom

1965; Shepard 1973), to those focused on providing systematic global to regional environment-specific classifications based on an inventory of determinative processes (*e.g.*, Coleman 1976; Reineck & Singh 1980 on delta forms; Fairbridge 1980 on estuaries; or Davies 1980 and Finkl 2004 on coasts globally), to those focused on regional to local details based on form and evolution (*e.g.*, Guilcher 1953; Schwartz 1972, 1973; Klein 1976), wherein, for example, rocky shores, sandy shores, and muddy shores are recognised and described (as summarised by Woodroffe 2002), or where coastal types at finer scales are recognised (*e.g.*, Semeniuk 1986). Many authors have focused on the details of coasts to the extent that there has been subdivision (classification) of coasts determined by geology, climate, oceanographic setting, and tectonic setting. Rocky shores in particular provide a good example of this. They have been studied and classified into types based on local determinative environmental factors, lithology, form and evolution (Bird & Dent 1966; Edwards 1941; Emery & Foster 1956; Emery & Kuhn 1982; Guilcher 1953; Hills 1949; Stephenson 2000; Sunamura 1992; Trenhaile 1974, 1980; Wentworth 1938), and limestone rocky shores specifically have been subdivided into numerous types based on lithology and morphology responding to climate and oceanographic setting. As Finkl (2004) points out, over-arching classifications are broad in scope but lack specificity, while specialised studies are narrowly focused and provide uneven coverage of coastal taxonomic units.

From a global perspective, the classification of coasts has been approached from that involving tectonics (and later, plate tectonics), with smaller-scale coastal features determined ultimately by their location in relation to tectonic plates, *viz.*, collision coasts or trailing coasts (Inman & Nordstrom 1971), or that of submerging coasts, neutral coasts, and emerging coasts (Johnson 1919). They have also been categorised from a perspective of accretionary *versus* eroding coasts; and that of primary youthful coasts *versus* secondary coasts; amongst others. From a scaler point of view, classifications have been approached from the largest scale, as outlined above, to the smaller scales, with classification of shore types based on response to waves, tides, climate, and rock types (see specific studies presented in King 1972; Schwartz 1972, 1973; Klein 1976).

A review of literature indicates that while inventories of coastal features have been generated for purposes of geoheritage/geoconservation (*e.g.*, Kiernan 1997), and coasts of geoheritage significance have been identified at specific locations on an *ad hoc* basis (*e.g.*, a range of internationally- and nationally-significant coasts in the United Kingdom, cited in Soper 1984, Bennett 1989, and Sale *et al.* 1989; as well as locations in Australia such in Victoria, see White *et al.* 2003, and at Hallett Cove in South Australia, see Parkin 1969; Dexel & Preiss 1995), a classification of coasts for the purposes of identifying features of geoheritage significance, to date, has not been systematically undertaken. This is a difficult endeavour. Firstly, because of the reason of scale: large coastal tracts (*i.e.*, megascale features) may be of geoheritage significance, especially from a global perspective (*e.g.*, the ria shores of the Kimberley Coast of Western Australia), while at the other extreme, smaller-scale features, at crystal scale, also may be significant. Secondly, coasts may be simple in form, lithology and structure, or they may be complex, or may be multi-genetic. Marine erosion, for instance, may result in a wide range of coastal types and complex coastal forms: coastal erosion may be incising into fairly uniform bedrock resulting in a range of differential responses dependant on the lithology (*viz.*, relatively resistant such as granite, or relatively soft such as friable limestone), but if rock types are heterogeneously distributed, the eroding coast results in a diverse suite of products and coastal forms. Marine erosion also may exhume landforms and geological features that were formerly buried: for example, a terrain of granitoid/gneiss inselbergs, surrounded by younger, softer sedimentary materials, through marine erosion, results in a headland-and-(sandy)-cove system where resistant inselbergs form large, rounded headlands, and the sedimentary materials, having eroded away, form the sandy coves. Thirdly, coastal types commonly are intergradational, with gradational lineages often being multidimensional, and this particularly renders classification complex. For instance, coasts grade from those wholly developed by marine inundation of the hinterland (with terrestrial forms still apparent) to eroded coasts with remnants of the original inundated morphology, to those dominated by erosional features, or a gradational suite of coasts ranging from recently-inundated to partly sediment-buried coasts to coasts wholly constructed by sedimentary processes. Complications in developing or applying a classification also arise because, depending on the scale of reference or observation, many features can be assigned to more than one category of coastal type.

Apart from some detailed work on rocky-shore types (cited above), the classification of estuaries (Fairbridge 1980), depositional forms such as beaches, coastal dunes, barriers, bars, and spits (Schwartz 1972; 1973, 2005) and tidal flats (Klein 1976; Reineck & Singh 1980; Semeniuk 1981b; 2005), which provide information on smaller-scale processes, products, and geodiversity, the classifications of coasts and coastal forms at the larger scale cited above have not been useful for categorisation of sites of geoheritage significance. They tend to be conceptual models developed to understand coastal setting and coastal evolution, and while they provide a framework for understanding the development of coasts, they are not product-oriented for smaller-scale features, and are not applicable for comparative geoheritage assessment at finer scales. For example, Davies (1980) provides a useful categorisation of coastal types based on integrating a range of features such as wave climate and tidal regime, distribution of shores types and climate, but the classification cannot be used at the site-specific scale.

A classification of coasts for purposes of identifying sites of geoheritage significance and for geoconservation has to be able to transcend a wide variety of coastal forms, from rocky shores and cliffs to depositional coasts, and their variety, to be able to encompass the variety of rocks types and materials presented at the shore, to deal with the variety of processes at the coast, and also to accommodate the variety of scales at which natural history features occur at the coast. It must also address that fact that a given tract of coast may be of geoheritage significance for a number of different reasons: for features of crystal size, to small-scale geomorphic features, to diagenetic products, to large-scale features of coastal form, or stratigraphy, or structure. None of the coastal classifications designed to date have been applicable in this manner.

The main processes leading to development of coastal types

To provide a context for the development of category-oriented coastal types for Western Australia, the main end-member processes that develop the different coastal forms and shore types are described. Identifying the main end-member processes ensures that all forms of coasts are captured at a high order level of classification.

In Western Australia, there are five main and ubiquitous end-member marine and coastal processes that develop coastal forms and shore types (Table 1); listed in generally decreasing scale, these are:

- marine inundation
- erosion
- sedimentation
- biogenic processes
- diagenesis

Globally, there are two other processes that can form coasts, though they are not strictly marine, *viz.*, volcanism and glaciation. Volcanism builds islands (with their peripheral coasts), or through ash accumulation, cone accretion, or lava flows encroaching from a mainland into the sea, develops coasts constructed of volcanic materials. Glaciers can erode coasts (thus overlapping with erosion), deliver sediments to the coast (thus overlapping with sedimentation), or form ice cliffs. These additional processes do not occur in Western Australia, and are outside the scope of this paper, but are mentioned for completeness in the list of coastal types (to be described later).

Essentially in Western Australia, all coastal forms and products of (marine) inundation, erosion, sedimentation, biological coastal construction, and diagenesis are underpinned by the five end-member processes operating alone, in combination, or operating at different scales. A given tract of coast may have products of these processes developed to different extent and scale along the shore, and/or may have products of these processes alternating along the shore. These end-member processes are described below as to their significance in developing coastal types. The scales at which the processes operate are shown diagrammatically in Figure 1.

Marine inundation is a major factor in developing coastal landforms. If there has been no Holocene erosion or sedimentation, or only minor erosion or sedimentation superimposed on such coastal landforms, marine inundation would be *the* major determinant of a coast form. At the larger scales, where erosion and sedimentation are secondary factors in coastal development in that they influence the formation of smaller-scale products, marine inundation in fact is a primary deciding factor in the development of coastal forms. An idealised diagram showing coastal forms initially developed by marine inundation of a topographically variable fluvially dissected hinterland, and some of the more common coastal forms developed by variation in erosion and sedimentation is presented in Figure 2.

Erosion is a ubiquitous process along the shore, and is another major determinant in the formation of many types of coastlines. With waves, tides, currents, chemical solution, and bioerosion as drivers, it can be a major determinant of coastal form. Coastal erosion cuts into mud deposits (*e.g.*, King Sound tidal flats; Semeniuk 1981a), sand deposits (*e.g.*, sand cliffs cut into Peron

Table 1

The five main end-member processes and resultant coastal forms in Western Australia

Process	Examples of resultant coastal form or product
Marine inundation	coastal form reflecting pre-inundation topography (*e.g.*, fluvially-dissected landforms that will develop a ria coast, or shore-parallel limestone ridges which will develop a limestone barrier coast)
Erosion	straight-cliffed coasts, crenulated cliffed coasts, coves and embayments, headlands, stacks, benches, platforms, notches, lapiés, fissures
Sedimentation	deltas, beach-ridge plains, barrier islands, beach/dune shores, tidal deltas, spits, cheniers, fans, breccia/talus deposits
Biogenic processes	coral reefs, serpulid reefs, oyster reefs, stromatolitic reefs
Diagenesis	beach-rock ramps, cemented pavements, breccia pavements, gypsum pavements, gypsum crystal meshworks, sheets of gypsum rosettes, patina

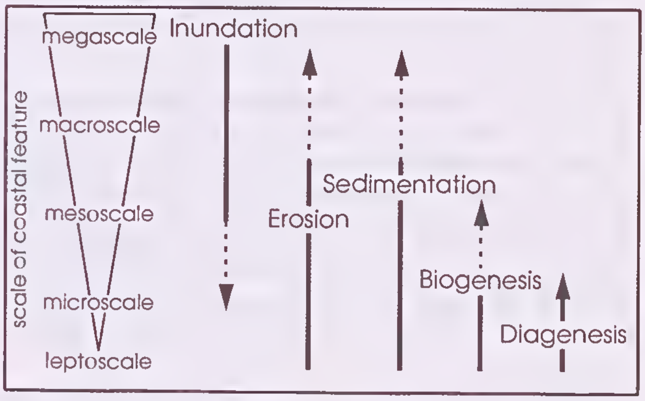


Figure 1. The five main end-member coast-forming processes in Western Australia with respect to scale. Marine inundation develops coastal forms mainly in the megascale to mesoscale range, and to a limited extent, at microscale. Erosion and sedimentation operate mainly at leptoscale to the mesoscale/macroscale, and to a limited extent, at megascale. Biogenic processes develop and influence coastal form mainly at mesoscale to leptoscale, while diagenesis develops and influences coastal form mainly at leptoscale and microscale.

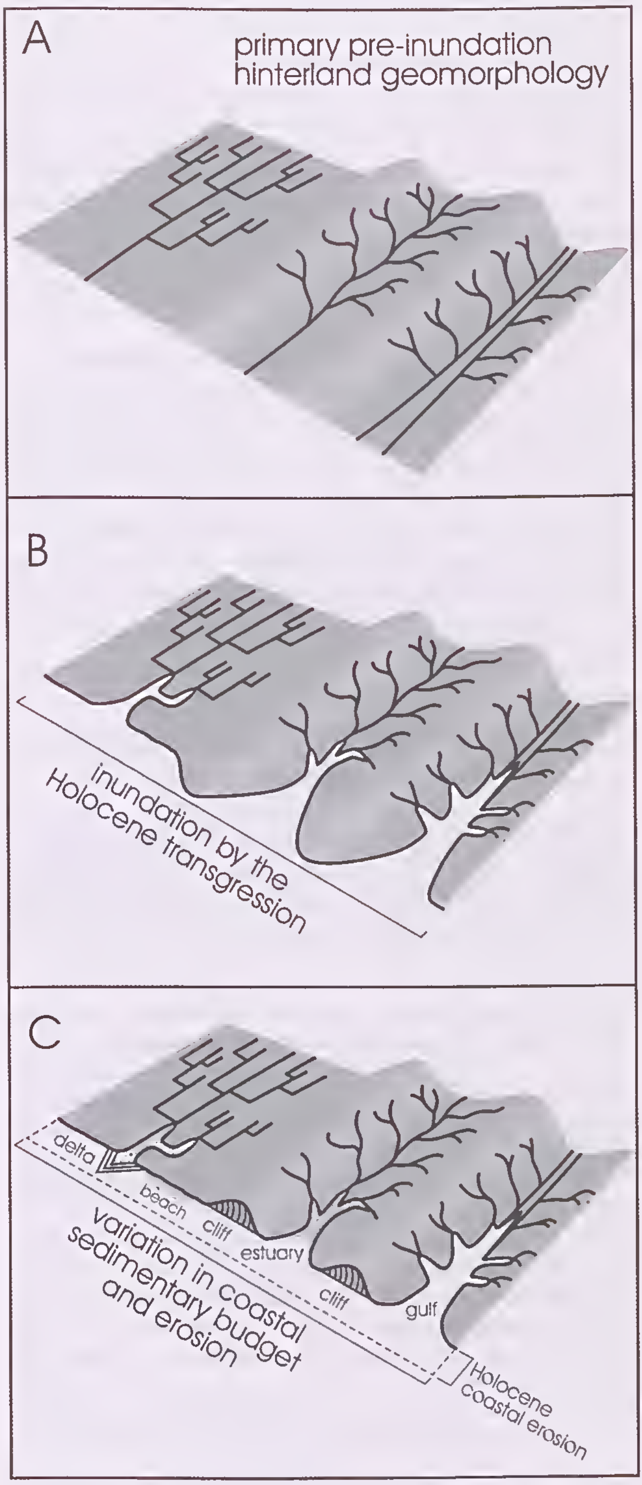

A
primary pre-inundation hinterland geomorphology
B
inundation by the Holocene transgression
C
delta
beach
cliff
estuary
cliff
gulf
variation in coastal sedimentary budget and erosion
Holocene coastal erosion

Figure 2. Diagram using a fluvially-dissected landscape as a template showing coastal forms developed by inundation and other processes, with the initial development of coastal form by inundation, followed by its modification by erosion and sedimentation. The same processes can, in principle, be applied to other landscapes. The juxtaposition of the three drainage basins are not meant to imply that such a situation exists in Western Australia or elsewhere, but to illustrate the range of hinterland forms that may be inundated by the Holocene transgression.

Sandstone; Logan *et al.* 1970), soft rock sequences (*e.g.*, cliffs cut into the Toolinna Limestone along the Nullarbor Plain), hard rock sequences (*e.g.*, cliffs cut into the Precambrian rocks along the Leeuwin-Naturaliste ridge), and into heterogeneous geological sequences (*e.g.*, coasts eroding a plain comprised of Tertiary sediment and protruding granitic inselbergs such as the Esperance Plain). Erosion exposes formerly buried geological features, and if it is differential where it incises into a lithologically- and/or structurally-variable bedrock, it results in complexly shaped shorelines (*e.g.*, the folded rocks of the King Leopold Mobile Zone in the southern Kimberley region). At one extreme, coastal erosion results in high rocky cliffs, with well-exposed geological sequences, and eroding sedimentary deposits at the other. It operates at the large scale to develop laterally-extensive cliffs such as the Zuytdorp Cliffs along the Carnarvon Basin Coast (see later), and the Baxter Cliffs along the edge of the Nullarbor Plain, and at the smaller scales to develop site-specific cliffs and local cliffs within a marine-inundated coastal terrain, or within a sedimentation-dominated coast.

Where sediment supply is adequate, regardless of whether it is marine-derived and directed shorewards, or land-derived and directed seawards, sedimentation can dominate the development of coastal form. It can be an extensive and ubiquitous process along the shore, developing many types of shores. For example, at the larger scales, sedimentation results in deltas, gulf and embayment fills as estuarine deposits, barrier dune systems, aeolian coasts, prograded beach/dune shores, and tidal flat systems. In Boreal and Arctic regions, coastal sedimentation can be driven by glacial processes. Sedimentation at the smaller scales, even if occurring within a dominantly eroding coast, results in shoreline spits and bars, pocket beaches, shoreline breccia deposits, and perched dunes. As such, sedimentation can be a major determinant of coastal form.

Erosion and sedimentation, alternating at various time frames from millennial, and greater than decadal, to daily, can result in a range of coastal forms. At large scales, it may be manifest in features such as channel switching in deltas, rows of cheniers on prograding tidal flats, truncation of beach-ridge lines, and development of inland-transgressing parabolic dunes on accreting sandy coasts. At smaller scales, it can result in complex geometry of recurved spits, talus or breccia deposits at the foot of cliffs, and the daily formation and destruction of beach cusps and rip channels (and their attendant stratigraphic and sedimentary products), amongst others.

Biogenesis involving biogenic processes and skeletal production can result in *resistant* shore-face biogenic structures, such as coral reefs, serpulid reefs, or oyster reefs, which may be expressed as extensive shore-face features, or as patch reefs. Generally, while many biologically generated resistant structures and accumulations (such as coral reefs) are subtidal features, and would not be strictly considered as "coastal", some are very shallow subtidal or may shoal into the low intertidal zone (being exposed at low tide), and form biogenic coasts. These can develop into fringing reefs that are border landmasses and islands. But while biogenic processes as coast-forming are included where reefs are concerned, we consider that most biological activity and contributions along the coast to be a subset of sedimentation, erosion, and diagenesis. For example, macrobenthos shell production, and other microfaunal and microfloral skeletal production, contribute materials to develop skeletal gravel and sand, or carbonate or siliceous mud, and form sedimentary deposits, with some shell production resulting in (sedimentary) biostromes. In this context, biogenesis (and biogenic activity) is part of sedimentation. The many other forms of biological activity in the coastal zone are subsets of erosion (*viz.*, bioerosion), or diagenesis (*e.g.*, algal boring of carbonate grains, or biologically mediated blackening of grains) and clearly not part of the processes that form coasts and shore types.

Diagenesis is the chemical, physical, or biological alteration(s) effected in sediments after their initial deposition, and during and after their lithification (Bates & Jackson 1987). Chemically, it involves precipitation, solution, or chemical/mineral reactions. Diagenesis can result in the development of a diagenetic rock (or *diagenite*; Bates & Jackson 1987). It will also include alteration of sedimentary rock such as Quaternary limestone. As a process, it can be instrumental in developing coastal forms, especially at the medium, small and fine scales, and many coasts and coastal geological features are diagenetic in origin, or have formed as the result of erosion and/or sedimentation acting in combination with diagenesis. Diagenesis is particularly important in developing coastal features along tropical and subtropical arid coasts, where, for example, tidal cementation of sand develops indurated shoreline ramps of beach rock. Diagenesis in Shark Bay results in the cementation of high-tidal sediments to develop extensive crusts and breccia pavements that dominate the shore. In combination with erosion and sedimentation, it can form distinctive shoreline products (*e.g.*, beach sand cementation forming beach rock, followed by cyclone-induced erosion of the beach rock to form slabs, and shoreward transport of the slabs to form a high-tidal shoreline ribbon of boulder conglomerate and breccia; Semeniuk 2008).

While marine inundation, erosion, sedimentation, and some aspects of organic reef-building have been identified previously by other authors as coastal-forming processes, to date, diagenesis in developing coastal features has not been given enough emphasis, *and has not been previously described as a significant coast-forming process*. While recognised as a process in modifying sediments, particularly at the grain-scale and structure-scale, and is demonstrably a prevailing and ubiquitous process in the coastal zone, diagenesis can be secondary but important to the other coast-forming processes (*e.g.*, coastal erosion cutting cliffs in relatively porous limestone is accompanied by diagenesis: the splash zone and the interface between marine water and fresh water are zones of cementation that form hard bands manifest as pavements, platforms, and benches). Diagenesis can result in significant and extensive coastal features, and can influence the development of coastal form, and the evolution of a coast. For this reason, in this paper, products of diagenesis are included where they influence coastal form and coastal features.

Coastal classification can be complex because coasts are formed not by a single process but by a range of processes operating at different scales, and to differing extent. The five major coastal-forming processes outlined above largely can act alone, or in combination, and contribute to a different individual extent when in combination. Coasts geomorphically also can express a gradational trend in their process of formation: from (marine) inundational to erosional to depositional. This gradational trend is from inundated landscapes, where the primary pre-inundated landscape is still evident, regardless of the geological nature of the inundated hinterland, to those where erosional forms dominate the coastal morphology, to coasts that are partly erosional/depositional, and finally, to those which are wholly depositional.

Within any suite of coastal forms, sedimentation and/or erosion, and biogenic and/or diagenetic processes, can result in coasts that express geohistorical features useful to reconstructing the history of the Earth, from Holocene to the Precambrian (*viz.*, Holocene stratigraphy underlying prograded coasts, or Holocene erosional morphology such as rocky shores with platforms and benches, or where erosion acting on older, pre-Holocene rocks have provided well exposed lithologies, structures, and stratigraphy, *e.g.*, sea cliffs exposing pre-Holocene stratigraphy).

Proposed hierarchical approach to the categorisation of coasts

While the approach to coastal classification designed in this paper is based on the Western Australian coast, if national and international comparisons are to be made for assessing geoheritage significance, it also needs to be applicable to other parts of Australia, and globally.

Coastal forms with their variable geological content and geomorphic expression are very different in various parts of the World dependent on geological setting, history of the landforms, type of hinterland geomorphology, and climate and oceanographic processes. For instance, solely from a geological perspective, a sea cliff of geoheritage significance in England, portraying Mesozoic chalk stratigraphy, palaeontology and ichnology has different attributes to a sea cliff cut into Mesozoic sandstone in Western Australia. Similarly, from a sedimentologic, climate and oceanographic perspective, mesotidal terrigenous mixed sand-and-mud tidal-flat deposits in sub-Arctic regions have very different sets of processes, products and detailed structures from those in mesotidal carbonate-dominated or mixed sand-and-mud tidal flat deposits in tropical arid regions (Reineck & Singh 1980). The mixed sand-and-mud tidal flats of Dampier Archipelago are different in tidal range, stratigraphy, small-scale products and sediment composition from carbonate-dominated tidal flats of the Canning Coast (Semeniuk & Wurm 1987; Semeniuk 2008). Coasts will respond to environmental settings developing different forms dependent on oceanography, tidal regimes, and climate. Thus, simply identifying a coastal form as a "sea cliff" or a "tidal flat" is insufficient to provide information for assessment and comparison for geoheritage and geoconservation purposes within a nation and certainly internationally. Clearly, classification of coastal features and coasts needs to address the global and national variation in coastal features in their geological, climate, and oceanographic setting.

At the next level, coasts develop various forms in response to the main coastal processes of marine inundation, erosion, sedimentation, biogenesis and diagenesis. These processes are instrumental in developing coastal forms and different types of coasts regardless of where the coast is located geologically, climatically or oceanographically. The coastal forms or coastal types generally will be ubiquitous and/or recurring, because the processes are ubiquitous.

Finally, there may be a range of smaller-scale features of a coast that are particular and peculiar to a given location, because of the context of geological, climate and oceanographic setting, and the type of coast developed by the dominance or combinations of the processes of marine inundation, erosion, sedimentation, biogenesis, and diagenesis acting on the shore. For instance, for rocky shores, regardless of where they are developed, there may be palaeontological or ichnological (palaeo) biodiversity exposed on a shore platform in different parts of the World. There may be region-specific, large nodules/concretions of calcite, or phosphate, or iron/manganese, exposed on shore platforms. There may be petrified forests, or a range of sedimentary, igneous, deformational, or metamorphic structures well exposed on wave-washed rocky shores in different geological regions in different parts of the State, nation or the World. Similarly, in the arena of modern sedimentology, there is variation globally (Reineck & Singh 1980): the fine-scale sedimentary structures developed on a tropical arid tidal flat will contrast with those of Boreal or Arctic tidal flats (*e.g.*, the latter may contain ice crystal prints). Thus the more detailed, or finer-scale variation in coastal types will merely reflect the geological, climatic or oceanographical setting of the coast superimposed on the coastal types.

To address this State-wide to international variation, the classification of coasts for purposes of assessing geoheritage significance and for geoconservation is approached in a three-level system:

Level 1: identification of the setting of the coast, geologically, climatically, and oceanographically; geological setting and environmental setting will determine lithological range, structural orientation, and any significant geological content, as well as climate effects, and wave and wind patterns, and tidal range; it will also determine the type of hinterland geomorphology that is presented to the coast;

Level 2: identification/classification of the various coastal types developed by the processes of marine inundation, erosion, sedimentation, biogenesis, and diagenesis to provide consistent comparative information for coastal description and assessment, and to provide a framework for finer-scale coastal features in a consistent context for describing, comparing and assessing sites of geoheritage significance; this level also identifies *types* of coasts of geoheritage significance;

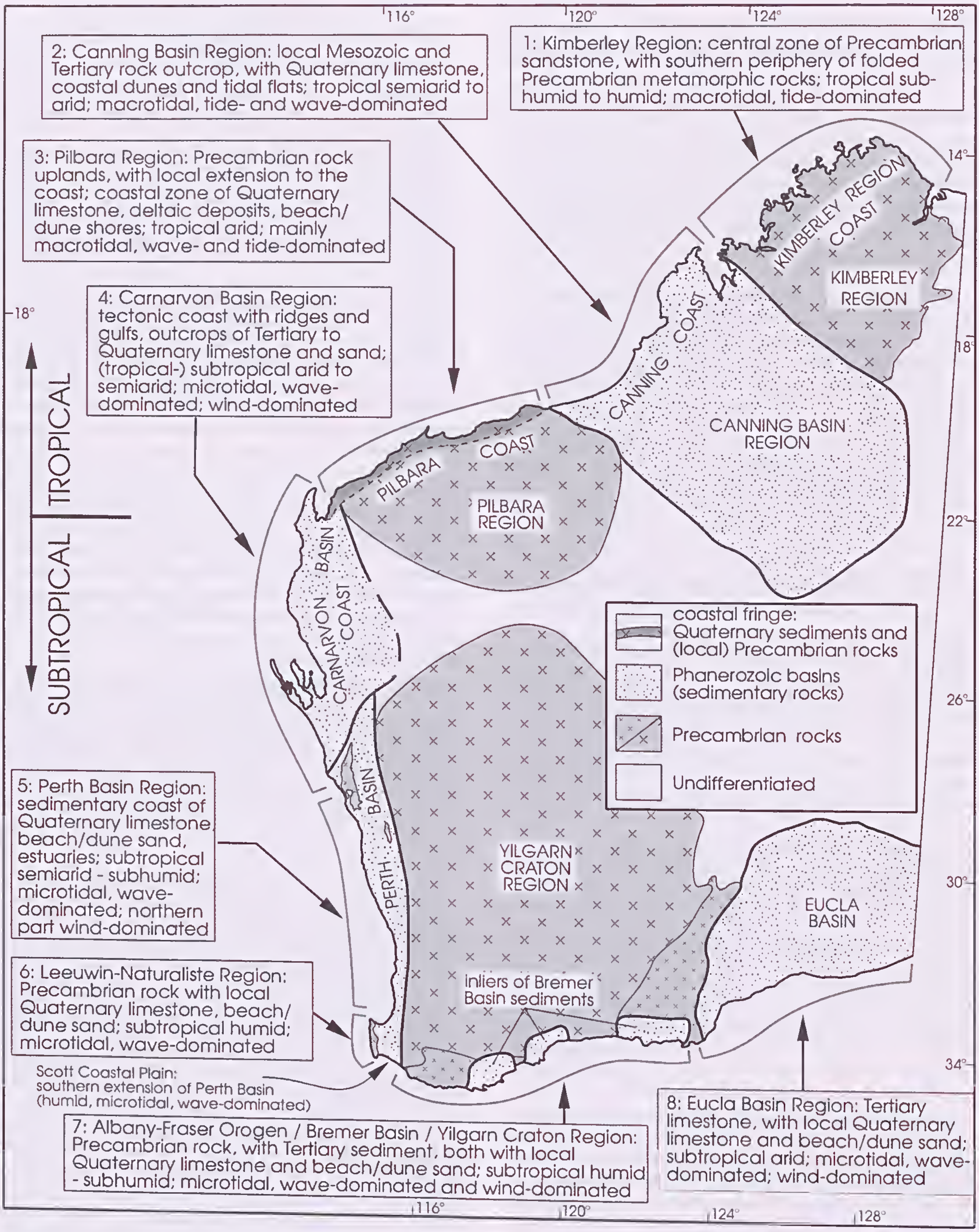
Level 3: inventory of finer-scale coastal features within the framework of coastal setting and coastal types identified by Levels 1 and 2.

Level 1 – locating the geological and environmental setting of coastal types regionally

In Western Australia, coasts are developed in different geological regions and different environmental settings, comprising latitudinally-varying climate and oceanography (Figure 3). In the first instance, geological region is a major factor underpinning what form a coast will develop in that it determines lithological range, structural orientation, and style of hinterland (*i.e.*, hinterland geomorphology) and the rock types exposed at the coast. Geological region also determines the tectonic and Holocene history of a region. Lithological sequences, and sedimentary, igneous, or metamorphic sequences in sea cliffs axiomatically will depend on the geological region being eroded, ranging, for example, from the interesting stratigraphy of a Silurian fluvial to estuarine system (*e.g.*, the Tumblagooda Sandstone at Red Bluff, Kalbarri) to Mesozoic fluvial to shallow marine systems (*e.g.*, the Broome Sandstone at Gantheaume Point, Broome) to Precambrian igneous rock sequences in the Dampier Archipelago, to complexly folded Precambrian rocks in the King Leopold Mobile Zone of the south-western Kimberley region (with fold structures determining coastal orientation and coastal form), to complexly folded and faulted metamorphic rock sequences in the southern coast regions. In this context, the geological, climatic and oceanographic categorisation of a coast is to some extent scale-determined as geological, climate, and oceanographic regimes are subcontinental features.

The five coastal-forming processes described earlier can be operating on varying types of hinterland geomorphology and geological materials (*e.g.*, marine inundation of a geologically-complex, high-relief, dissected hinterland, or inundation of a relatively geologically simple high-relief dissected hinterland, or inundation of a geologically complex relatively low-relief dissected hinterland, and so on), with inundation, or erosion, or sedimentation dominant.

In Western Australia we recognise eight coastal sectors, broadly corresponding to geological regions, that determine coastal form; these are the Kimberley Region (Kimberley Basin bordered by the Halls Creek Mobile Zone and King Leopold Mobile Zone), the Canning Basin Region (Canning Coast), the Pilbara Region (Pilbara Coast), the tectonically active horst-and-graben complex of the western Carnarvon Basin with its coastal ridges-and-gulfs, and then progressing southwards through a variety of geological regions such as the Perth Basin, the Leeuwin Complex, the south coast between Augusta, Esperance, and Israelite Bay (with Precambrian rocks of the Albany-Fraser Orogen and Yilgarn Craton, and sediments of the Bremer Basin), and the Eucla Basin (Geological Survey of Western Australia 1975, 1990; Playford *et al.* 1976; Myers 1994). Key aspects of the geology of the regions are summarised in Table 2 and Figure 3. The focus in Table 2 is not on Holocene coastal sediments and their geomorphic expression, as these may be repetitive in form and content, and change depending on oceanography and climate (from barriers with mobile parabolic dunes in the Leschenault Peninsula, to beach-ridge plains in the Rockingham area, to tidal flats along



1: Kimberley Region: central zone of Precambrian sandstone, with southern periphery of folded Precambrian metamorphic rocks; tropical sub-humid to humid; macrotidal, tide-dominated

2: Canning Basin Region: local Mesozoic and Tertiary rock outcrop, with Quaternary limestone, coastal dunes and tidal flats; tropical semiarid to arid; macrotidal, tide- and wave-dominated

3: Pilbara Region: Precambrian rock uplands, with local extension to the coast; coastal zone of Quaternary limestone, deltaic deposits, beach/dune shores; tropical arid; mainly macrotidal, wave- and tide-dominated

4: Carnarvon Basin Region: tectonic coast with ridges and gulfs, outcrops of Tertiary to Quaternary limestone and sand; (tropical-) subtropical arid to semiarid; microtidal, wave-dominated; wind-dominated

5: Perth Basin Region: sedimentary coast of Quaternary limestone, beach/dune sand, estuaries; subtropical semiarid - subhumid; microtidal, wave-dominated; northern part wind-dominated

6: Leeuwin-Naturaliste Region: Precambrian rock with local Quaternary limestone, beach/dune sand; subtropical humid; microtidal, wave-dominated

Scott Coastal Plain: southern extension of Perth Basin (humid, microtidal, wave-dominated)

7: Albany-Fraser Orogen / Bremer Basin / Yilgarn Craton Region: Precambrian rock, with Tertiary sediment, both with local Quaternary limestone and beach/dune sand; subtropical humid - subhumid; microtidal, wave-dominated and wind-dominated

8: Eucla Basin Region: Tertiary limestone, with local Quaternary limestone and beach/dune sand; subtropical arid; microtidal, wave-dominated; wind-dominated

Figure 3. Simplified regional geological and environmental patterns of coastal Western Australia: distribution/description of geological regions, climate and oceanography patterns, and regional coastal sectors. Information from Gentilli (1972), Geological Survey of Western Australia (1975, 1990), Playford *et al.* (1976); Davies (1980), and Semeniuk (1993, 1995, 1996a). Note that the coast in the Scott Coastal Plain area is not another geological region but the southern extension of the Perth Basin.

the Pilbara Coast, and macrotidal beaches along the Canning Coast), but rather on the pre-Holocene geological character that will determine small-scale lithologic and geomorphic expression along wave-washed cliffs.

Coastal form can be determined by oceanography. Coasts may be extreme macrotidal, macrotidal, mesotidal, or microtidal (Davies 1980; Semeniuk 2005), and wave-dominated or tide-dominated, or protected (Figure 3). Northern Western Australia is extreme macrotidal and macrotidal, and semidiurnal, and to some extent wave dominated, with a maximum tidal range at King Sound, decreasing northwards and southwards to macrotidal between Port Hedland and the northern Kimberly area. Tidal range decreases to mesotidal and microtidal and semidiurnal towards south, until along the southern coast it is microtidal and diurnal. Oceanography determines the variation in extent that wave or tidal action develops coastal forms such as cliffs, or beach ridges, tidal creeks, rips, ridges-and-runnels, and cusps, amongst other products, and the extent that shore platforms and benches along rocky shores are formed at various tidal levels.

Additionally, coasts are influenced by the climate in which they reside (Figure 3). Northern parts of Western Australia are tropical and subhumid, with high evaporation, and enough rainfall to affect coastal margins *via* freshwater seepage and run-off. Climate changes southwards to tropical and subtropical arid, with high evaporation rates and minimal rainfall, to subtropical (near temperate) with moderate evaporation and high rainfall, and to subtropical arid along the south coast. Climate affects sea temperatures, with consequences on the production and solubility of carbonate grains, and carbonate precipitation (*viz.* skeletal production, limestone solubility, and diagenesis). The rainfall/evaporation ratio determines the amount of evaporation in the coastal zone, especially on macrotidal flats, and the amount of freshwater that is delivered to the coast in humid climates. Climate also determines whether the coast is wind-dominated, and the wind patterns, directions, and strength, with its attendant effects on coastal dunes, wind waves, and evaporation, the extent that dunes are mobilised, and that rips and cusps are developed. In this context, the southern and central western coasts of Western Australia are wind-dominated.

The oceanographic and wind climate regions in Western Australia are as follows (Figure 3): the north-west coast of the Kimberley region, the Canning Coast and Pilbara Coast, the Carnarvon Basin Coast[2] and northern Perth Basin Coast, the southern Perth Basin Coast, and the south coast

Table 2

Summary of the geology/lithology of the geological regions along the coast

Region	Diagnostic pre-Holocene geological features at the coast
Kimberley	central region (Kimberley Basin) of Proterozoic sandstone, basalt, siltstone, and basic intrusive rock, and a tectonic periphery (King Leopold Mobile Zone) of deformed igneous, metamorphic and sedimentary rock including greywacke, basalt, siltstone, acid volcanic rock, basic intrusive rock and granite
Canning Basin	Mesozoic sandstone with an abundance of diverse sedimentary structures; locally, Tertiary sediments, Pleistocene calcarenites, and Pleistocene red sand
Pilbara	Precambrian granites, and folded to layered greenstones, cherts, and ironstones, and dolerites, volcanic rocks; coastal fringe of Pleistocene limestone, red sand, and conglomerate
Carnarvon Basin	largely horizontally layered Tertiary marine limestones, locally Silurian sandstone (with an abundance of diverse sedimentary structures), red to yellow quartz sand; Pleistocene limestone (seagrass facies, beach/dune facies, coral reefs, pedogenic materials, and rocky shore sequences)
Perth Basin	Pleistocene limestone (calcarenites) composed of seagrass facies, beach and dune sediments, rocky shore sequences, and coral reefs
Leeuwin Complex	granite, anorthosite gneiss and amphibolite strongly deformed (folded, faulted, and sheared) and recrystallised to granulite facies
Albany-Fraser Orogen / Bremer Basin / Yilgarn Craton	Yilgarn Craton in its southern region: granite and gneiss Albany-Fraser Orogen: amphibolite to greenschist facies sedimentary protolith gneisses, migmatites and granites, with tectonic structures related to subduction processes and prolonged strike-slip tectonism (folded, faulted, and sheared); Bremer Basin: largely horizontally layered sandstone, siltstone, spongolite
Eucla Basin	horizontally layered bryozoan calcarenite, and locally developed shore-parallel coastal and aeolian deposits

From Geological Survey of Western Australia (1975, 1990), Playford *et al.* (1976) and Myers (1994).

---

[2] Traditionally, geographically, various tracts along the mid Western Australia coast encompassing Geraldton, Kalbarri, Zuytdorp Cliffs, Shark Bay, and extending to the Ashburton River have been variably known as the "Batavia Coast", the "Coral Coast", and the "Gascoyne Coast", with formalisation of the latter as the "Gascoyne Bioregion". The term Carnarvon Basin Coast is used here for the tract between Kalbarri and North West Cape (in lieu of "Gascoyne Coast"), corresponding to the location of the Carnarvon Basin and in keeping with a nomenclature reflecting that geological region controls coastal form (Semeniuk 1993). Linking the coast nomenclature to the Carnarvon Basin (with its tectonic control of coastal form) better reflects regional structure of this coastal sector.

Level 2 – category-oriented classification of coastal types developed by the five coast-forming processes

The category-oriented classification of coastal types has been designed to classify a wide variety of settings. It has involved identifying the range of coastal forms (*i.e.*, types of coasts, formed as products of the main end-member processes), capturing all forms of coasts at a high order level of classification, and provides a framework within which sites of geoheritage significance can be consistently compared and assessed. To relate the coastal features to a scalar frame we use scale descriptors, thus ensuring that not only are coastal types and coastal features captured at all scales, but that similar coastal forms expressed at different scales also are captured.

Types of coastal forms and/or geological features developed at the coast

Given the main formative processes and their combinations outlined above, we recognise nine types of coastal forms and/or geological features developed in the coastal zone; these are:

Type 1: landforms developed by the post-glacial marine inundation of pre-existing landforms (the primary pre-inundated landscape is still evident);

Type 2: landforms developed by marine inundation of pre-existing landforms *and* coastal erosion of the bedrock geology, or hinterland landforms;

Type 3: landforms wholly developed by coastal erosion, or where erosion has totally or nearly totally overprinted primary (pre-transgression) hinterland landforms;

Type 4: coasts developed by the exhumation or isolation of older landforms and their geological features;

Type 5: coastal landforms developed by marine inundation *and* sedimentary infilling;

Type 6: landforms wholly constructed by coastal sedimentary processes that have been active during the Holocene;

Type 7: landforms constructed by Holocene coastal sedimentary processes that have superimposed erosional features;

Type 8: biogenic coasts; and

Type 9: coasts with dominant or conspicuous diagenetic features.

Furthermore, in order to recognise geohistory that may be manifest either within Holocene coastal features, or within pre-Holocene sequences, a further three types are required for identifying sites of geoheritage significance and for geoconservation.

Type 10: erosional coasts recording Holocene sea-level history;

Type 11: Holocene depositional coasts recording sedimentary history, ocean history, climate history and sea-level history; and

Type 12: sea cliffs exposing lithology, stratigraphic sequences and contacts, and structure.

While these classification categories were developed within Western Australia, Types 1–12 can be recognised worldwide. However, as noted earlier, there are two additional types occurring globally but not represented in Western Australia. They are added here as Types 13 and 14 for completeness. Type 13 is a volcanic coast, formed by Holocene volcanism. It is analogous to sedimentary coasts, but accretion, progradation, and coastal development is driven by volcanism not sedimentation. Type 14 is a glacial coast (an ice coast), where ice sheets and ice cliffs form coasts. Glacial coasts do not include glacigenic sedimentary coasts.

Coastal Types 1–7 and their inter-relationships are summarised diagrammatically in Figures 4 and 5, and placed in groups showing the intergradation between them (Figure 6). Types 1–7 are morphological stages with a trend towards increasing erosion on one hand, and a trend to increasing sedimentation on the other. Being intergradational, they are placed in a quasi-chronological order specifically to show their evolutionary stages following a marine transgression, and to show the sequence from erosion-dominant coasts to sedimentation-dominant coasts. Type 9 involves specific features developed by diagenesis. In all these coastal types that there will be variation in scale of the geological or geomorphological feature. Types 10, 11, 12, and in part Type 8 are special categories that manifest geological features useful to determining pre-Holocene Earth history, or sedimentary history, ocean history, climate history or sea-level history during the Holocene.

Types 1 and 2 overlap to some degree, but generally Type 1 is developed at the larger scale (*e.g.*, rias). Type 3, though expressed as large-scale features (such as sea cliffs along the edge of the Nullarbor Plain, or the Zuytdorp Cliffs), is best expressed at the fine to small scale (*e.g.*, benches along rocky shores). In many locations, Types 1, 2 and 3 are separated, because although often co-existing in the same region, they represent stages in coastal development from primary to fully eroded, and the types may be present at different scales within the same tract of coast. Types 1, 2 and 5 also are inter-related: marine inundation and erosion of bedrock along the coast can develop sedimentary accumulations that are linked to the pre-existing topography, and these sediments partly fill the embayments of Coastal Type 1 (*cf.* Semeniuk 1985a), or there may be development of cuspate forelands, and tombolos that capture eroding nearshore rocky islands. Types 5 and 6 overlap, reflecting increasing erosion of Holocene sedimentary materials.

As a product of the interaction of seawater, fresh water, evaporation and chemical reactions along the shore zone, Type 9, with fine- to small-scale diagenetic features, can occur in any of the other coastal types. On the other hand, it can also form a shore type in isolation (*e.g.*, beach-rock coasts where beach rock forms thick cemented deposits that dominate the shore).

There may be partitioning of some of the coastal types listed above across a shore. This is particularly the case for coasts with diagenetic features and biogenic features. That is, a given shore may have tidally-related zones of diagenesis or biogenic construction, *e.g.*, a sea cliff (Type 12), or a beach/dune system (Type 7), may have a coral reef along its low tidal zone, or a zone of distinct diagenesis, respectively.

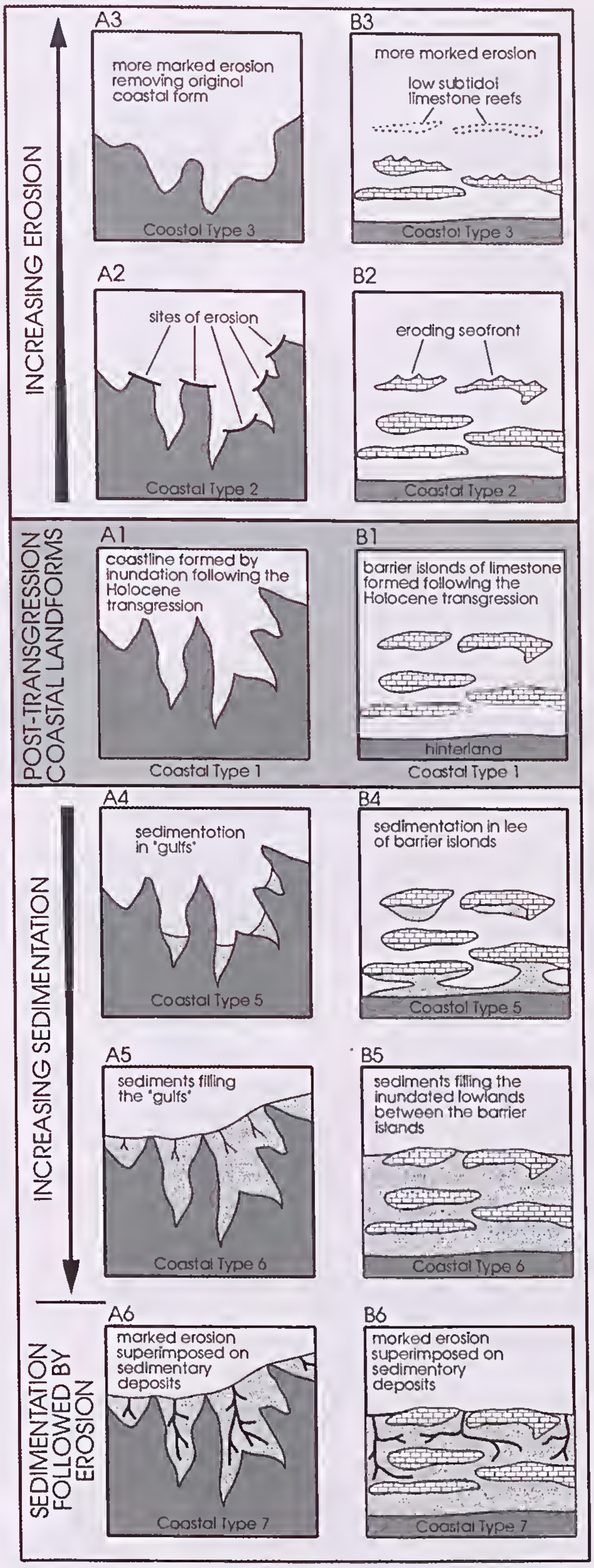

INCREASING EROSION
A3
more marked erosion removing original coastal form
Coastal Type 3
B3
more marked erosion
low subtidal limestone reefs
Coastal Type 3
A2
sites of erosion
Coastal Type 2
B2
eroding seafront
Coastal Type 2
POST-TRANSGRESSION COASTAL LANDFORMS
A1
coastline formed by inundation following the Holocene transgression
Coastal Type 1
B1
barrier islands of limestone formed following the Holocene transgression
hinterland
Coastal Type 1
INCREASING SEDIMENTATION
A4
sedimentation in "gulfs"
Coastal Type 5
B4
sedimentation in lee of barrier islands
Coastal Type 5
A5
sediments filling the "gulfs"
Coastal Type 6
B5
sediments filling the inundated lowlands between the barrier islands
Coastal Type 6
SEDIMENTATION FOLLOWED BY EROSION
A6
marked erosion superimposed on sedimentary deposits
Coastal Type 7
B6
marked erosion superimposed on sedimentary deposits
Coastal Type 7

Figure 4. Coasts developed by marine inundation and other coastal processes on a fluvially-dissected landscape (sequence A) and on a terrain of Pleistocene limestone ridges (sequence B). Examples of these coastal types are shown in Figure 8. The central coastal types have been developed by simple marine inundation (A1 and B1). One trend shows results of increasing effects of erosion (A2–A3, and B2–B3), the other shows increasing effects of sedimentation (A4–A5 and B4–B5), with the final diagrams (A6 and B6) showing later erosion superimposed on coastal landscapes formed by sedimentation.

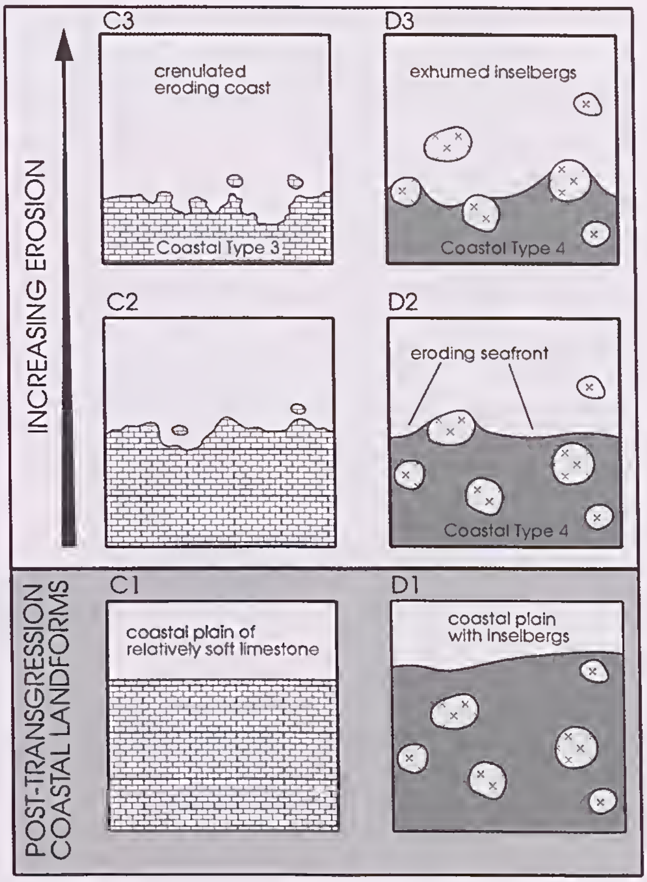


Figure 5. Coasts developed where erosion is dominant and has eliminated the pre-inundation morphology (gradation C1–C3), and where erosion has exhumed inselbergs (gradation D1–D3).

Type 12 is a special category of coast where erosion has particularly emphasised the lithological, structural and stratigraphic features of the local pre-Holocene geology. The rock types can range in age from Precambrian to Pleistocene.

In the above examples, there is emphasis on products, but there are extant processes that are still generating these products. What constitutes "dynamic processes" has been discussed earlier, encompassing those that are very active and conspicuously dynamic (such as ingressing mobile dunes, collapsing sea cliffs), to the slowly retreating cliffs, slowing advancing coasts, slow-acting chemical and bioerosion that nonetheless control and develop the small-scale and fine-scale geomorphic features at the coast. Regardless of rate and scale of process operating, it is the coastal process (or processes) *in action* that constitutes a dynamic environment.

The complex nature of coasts and the different geoheritage attributes of a coast mean that a tract of coast, from a geoheritage perspective, can be assigned to a number of categories of coastal type. Assignment to one category, however, does not mean exclusion from another. The Baxter Cliffs along the Nullarbor Plains can be assigned geomorphologically as an "eroding coast" *and* to the category of reference stratigraphic site or type section (Type 12) for the Toolinna Limestone at Toolinna Cove, as well as to the category that comprises fine- to

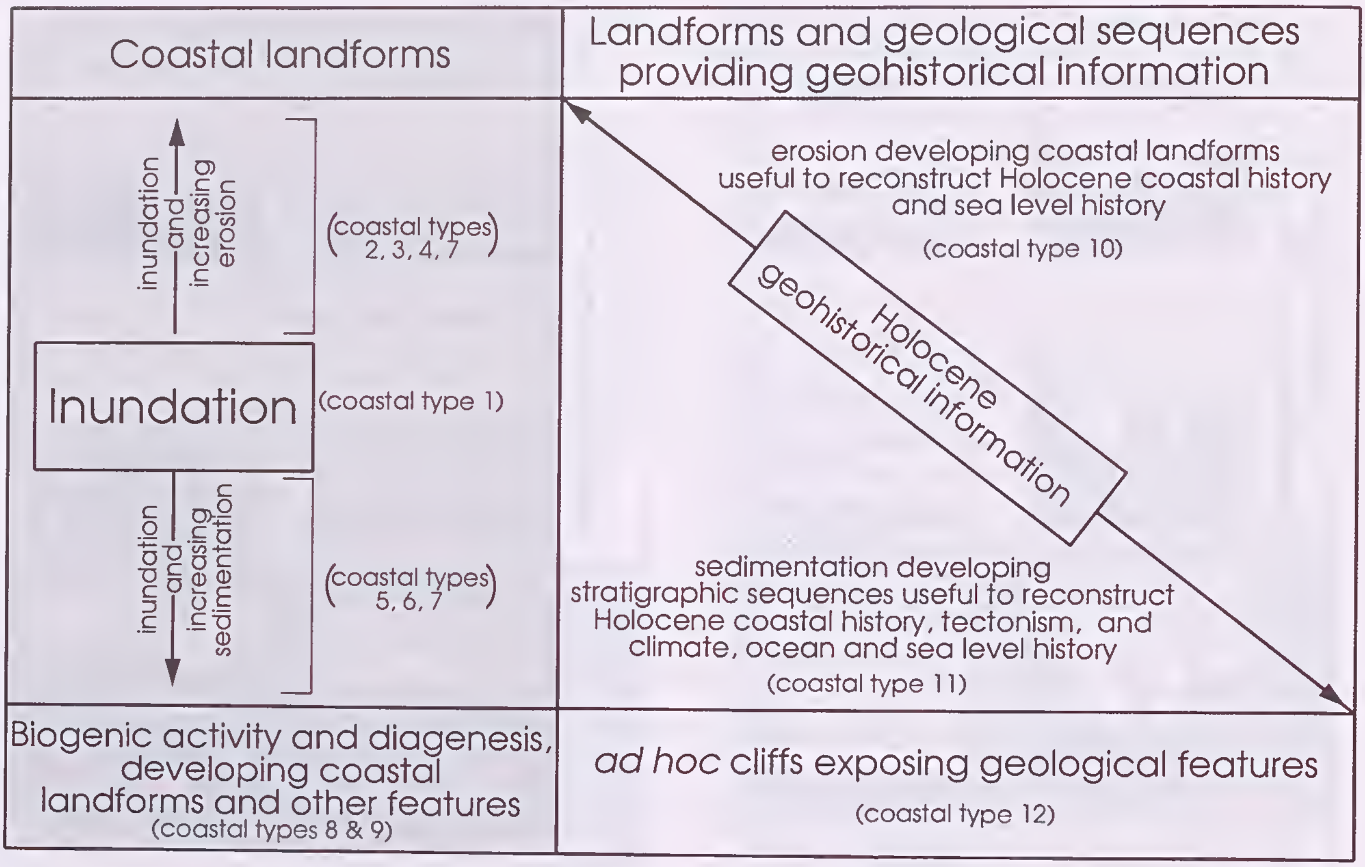

Coastal landforms
Landforms and geological sequences providing geohistorical information
inundation and increasing erosion
(coastal types 2, 3, 4, 7)
Inundation
(coastal type 1)
inundation and increasing sedimentation
(coastal types 5, 6, 7)
erosion developing coastal landforms useful to reconstruct Holocene coastal history and sea level history
(coastal type 10)
Holocene geohistorical information
sedimentation developing stratigraphic sequences useful to reconstruct Holocene coastal history, tectonism, and climate, ocean and sea level history
(coastal type 11)
Biogenic activity and diagenesis, developing coastal landforms and other features
(coastal types 8 & 9)
ad hoc cliffs exposing geological features
(coastal type 12)

Figure 6. The groupings of the 12 Coastal Types occurring in Western Australia. The suite of coastal landforms developed by marine inundation, increasing erosion and/or sedimentation, and biogenic activities and diagenesis, is grouped in the grey box, a group focused solely on modern *coastal landforms*. Geological features and sequences, Holocene sedimentary sequences, and earlier Holocene landforms that provide Holocene and pre-Holocene geohistorical information are placed into the second group.

small-scale diagenetic features formed along the coastal zone (in the development of a cemented rocky shore platform in this particular climatic and hydrological setting). Similarly, the Point Becher area can be assigned to the category of "landforms constructed by Holocene sedimentary coastal processes" (*i.e.*, the accreting beach-ridge plains, the coastal chaots, and the local ingressing parabolic dune), as well as to that of "depositional coasts recording sedimentary history, ocean history, climate history and sea-level history" (*i.e.*, the stratigraphy under the beach-ridge plain records sea-level history, ocean history, and climate history).

As mentioned earlier, for many of the types of coast, a given coastal feature can occur at different scales. The classification of coastal types, therefore, has been presented as non-scalar, and the identification of a coastal type or coastal features is not fixed to a given scale. In this context, coastal features identified and classified as to type can be related to a scale by a (geomorphic) descriptor (*viz.*, megascale, macroscale, mesoscale, microscale, leptoscale, or other size-equivalent term). Spits and rocky shores are used to illustrate coastal feature (or a coastal type) occurring at various scales (Figure 7).

Some coastal forms can be developed by erosion during a number of repetitive Quaternary transgressions, of which the current Holocene marine inundation (axiomatically) is the last in a series of such episodes. Hence, at the megascale and macroscale, coastal forms developed by erosion may be reflecting a number of Quaternary erosional episodes. This is most likely to develop where there has been marine inundation of dissected topography cut into hard rocks to develop ria shores, and hence the current ria form also is the Pleistocene form. Nonetheless, the Holocene transgression has inundated a Pleistocene topography, some of which may have been developed by Pleistocene coastal processes. With softer rocks, where erosion is rapid (*e.g.*, eroding limestones to form the Twelve Apostles in Victoria, and the Baxter Cliffs in southern Western Australia, and coastal Pleistocene limestone in southwestern Australia), this is not an issue because Holocene erosion actually is the determining factor in developing the coastal form.

Descriptions of these Coastal Types are provided below, largely drawn from Western Australian examples, but supplemented by other Australian and by international examples. Some of these Coastal Types are illustrated in Figures 8–10. In the descriptions that follow, the relationship of the types to the four categories of geoheritage of Brocx & Semeniuk (2007) is provided. Examples of coastal forms that are present within the twelve coastal types in Western Australia are provided in the description of each of the Coastal Types.

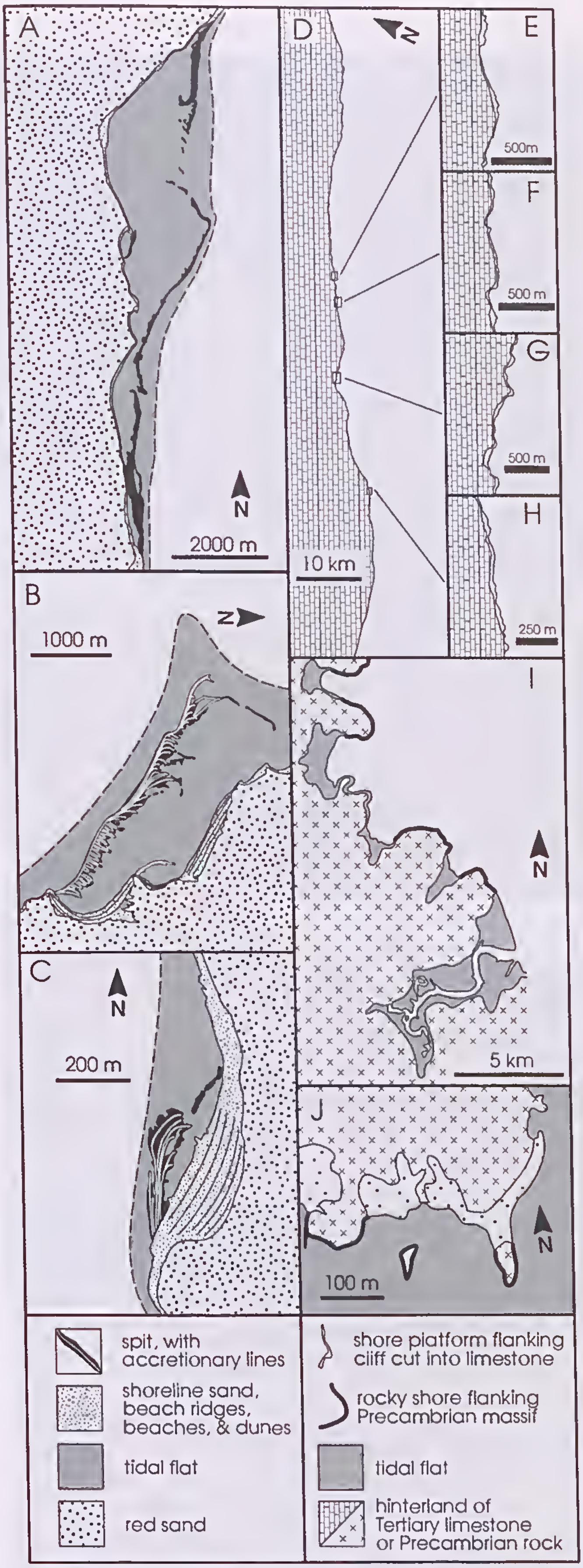

A
2000 m
N
B
1000 m
N
C
N
200 m
D
N
10 km
E
500m
F
500 m
G
500 m
H
250 m
I
N
5 km
J
N
100 m
spit, with accretionary lines
shoreline sand, beach ridges, beaches, & dunes
tidal flat
red sand
shore platform flanking cliff cut into limestone
rocky shore flanking Precambrian massif
tidal flat
hinterland of Tertiary limestone or Precambrian rock

Figure 7. A–C. Various sizes of spits in Shark Bay (east shore of L'Haridon Bight; northern Faure Island; and south of Eagle Buff). D–I. Various sizes and extent of rocky shores in Western Australia. D–G: The Baxter Cliffs, Eucla Basin. H: Port Warrander, Kimberley Coast. I: King Bay, Pilbara Coast. These examples illustrate coastal forms can have expression at various scales, from megascale to mesoscale.

Type 1: coastal landforms formed by marine inundation

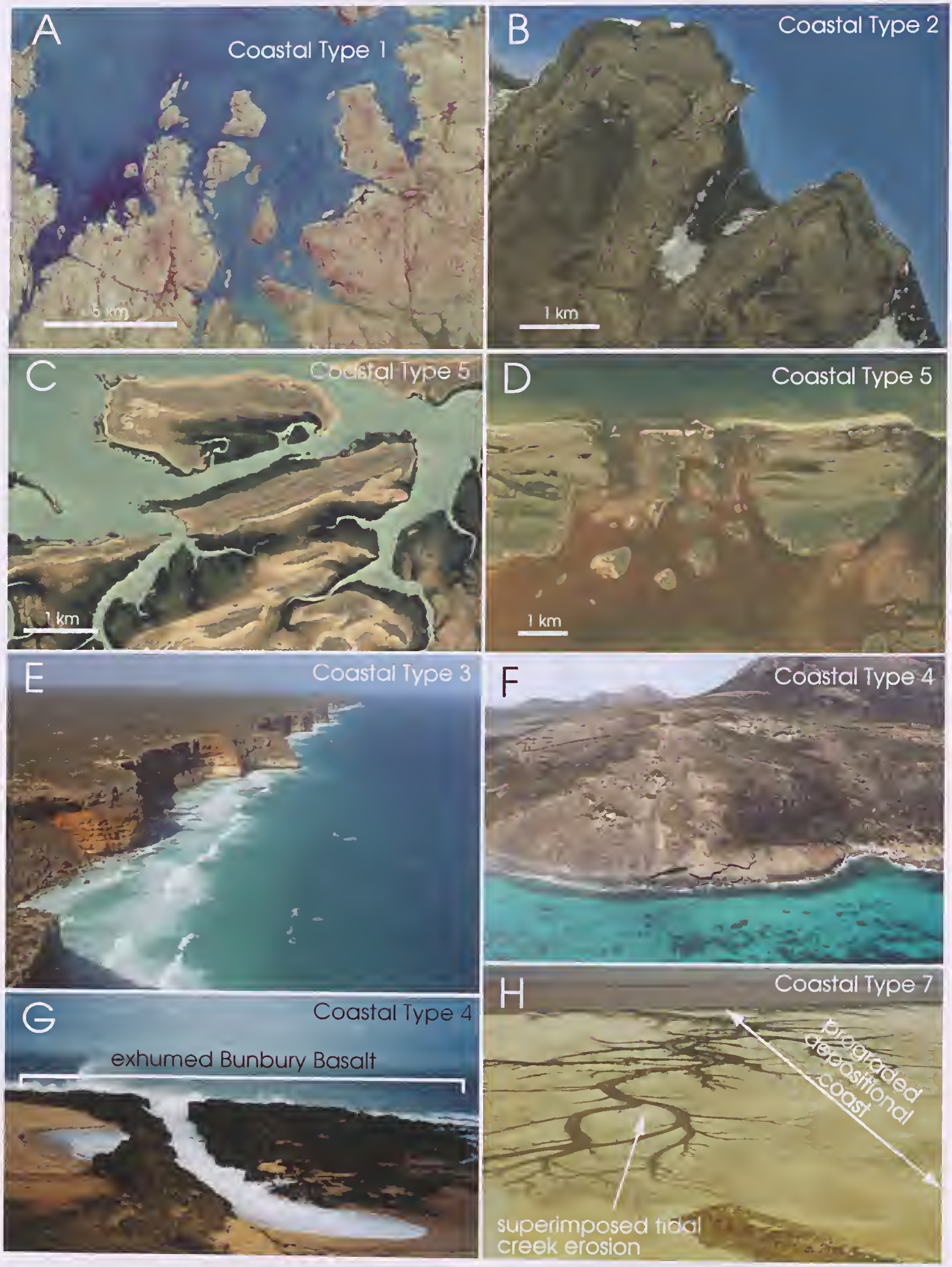
Coastal landforms developed by the post-glacial marine inundation of pre-existing terrestrial landforms, including those of Pleistocene age, vary from large-scale features to smaller-scale morphologic features. Examples from Western Australia of large-scale coastal landforms are the ria shores of the Kimberley Coast (which formed by the marine inundation of a fluvially-dissected terrain), the limestone barrier island complexes along the Pilbara Coast (Semeniuk 1996a), the complex coast of the Dampier Archipelago, and the gulf-and-peninsula morphology of Shark Bay. Examples of fine- to small-scale morphologic features are the inundated boulder slopes of the rocky islands of the Dampier Archipelago (Semeniuk *et al.* 1982), and some of the limestone barrier islands along the Pilbara Coast (Semeniuk 1996a), amongst others.

Coastal Type 1 can be assigned to the geoheritage category of *modern, active landscapes* in that coastal landforms developed by the post-glacial marine inundation of the landscape are extant.

Type 2: coastal landforms developed by marine inundation *and* coastal erosion

These are coastal landforms developed by the result of marine inundation of pre-existing landforms *and* coastal erosion of the bedrock geology, or hinterland landforms. Marine inundation develops the primary coastal type, and erosion develops finer-scale features therein. The erosional products vary in size from large-scale (such as marine cliffs) to small-scale features such as shore platforms and benches, or micro-morphologic features (such as micro-pinnacles and tafoni). Variation in style and form of coasts result from differing bedrock materials such as granite, shale, folded metamorphic rock, or limestone (*e.g.*, rounded shores, plunging cliffs, stepped platforms and benches, serrated platforms, or high tidal pavements cut into limestone by salt weathering), and the various coastal landforms developed by marine inundation of the pre-existing terrestrial landforms, examples at the fine- to small-scale features are platforms, benches, notches and micro-pinnacles cut into calcarenites exposed along the shores of Rottnest Island and the Perth region (Semeniuk & Johnson 1985; Playford 1988), and the extensive high-tidal limestone pavements formed by salt weathering of Pleistocene limestone barriers in the Pilbara region (Semeniuk 1996a). The emphasis here is that coastal erosion has modified the morphology of the coast after the post-glacial marine inundation, resulting in varying coastal forms from medium scale to small and fine scale. Some of the complexity of products of erosion are the result of marine erosion acting on lithologically-layered or heterogeneous rocks (*e.g.*, structural benches controlled by lithology such as horizontal shale beds, or horizontal, hard, sandstone beds), and some are due to the effect of marine planation and erosion, producing benches that are related to present and former Holocene sea-level positions, and modern climate setting and oceanographic setting.

Coastal Type 2 mostly can be assigned to the geoheritage category of *modern, active landscapes* in that coastal landforms developed by the post-glacial marine inundation of the landscape, and their erosion, are extant.


A
Coastal Type 1
5 km
B
Coastal Type 2
1 km
C
Coastal Type 5
1 km
D
Coastal Type 5
1 km
E
Coastal Type 3
F
Coastal Type 4
G
Coastal Type 4
exhumed Bunbury Basalt
H
Coastal Type 7
prograded depositional coast
superimposed tidal creek erosion

Type 3: landforms wholly developed by coastal erosion

These coastal landforms are wholly developed by erosion, or where erosion has totally or nearly totally overprinted primary (pre-transgression) hinterland forms. Sea cliffs are a common product of this type of coastal development, and these can vary from large scale, such as extensive and high sea cliffs, to smaller-scale cliffs, platforms and benches. At smaller scales along all scales of sea cliffs, there may be lithologically-determined structural benches and platforms, and benches, and platforms, smaller cliffs, and a variety of other fine-scale features (Semeniuk & Johnson 1985) determined by height of the shore relative to sea level in a given climatic/oceanographic setting.

Examples of this coastal landform are the modern crenulate cliffed coast cut into Tertiary limestone along the edge of the Nullarbor Plain in Western Australia (*e.g.*, the Baxter Cliffs), the modern retreating, crenulate, cliffed coast cut into Tertiary limestone in Victoria ("The Twelve Apostles"), and the smaller-scale cliffs, platforms and benches, along the seaward edge of limestone barriers of the Pilbara Coast (Semeniuk 1996a).

Coastal Type 3 can be assigned generally to the geoheritage category of *modern, active landscapes.*

Type 4: coasts formed by the exhuming or isolation of older landforms

These landforms have been developed by coastal erosion, exhuming or isolating formerly buried landforms and other geological features. The coastal landform usually is derived by the exhuming of a relatively large geological feature, and should dominate the coast, not merely be part of a hard band or other more resistant layer or band within a sedimentary, metamorphic or igneous system. Examples are inselbergs, or volcanic plugs that are embedded in less durable materials and that through coastal erosion, have been exhumed or isolated. Such landforms can vary from large scale (such as granitic or gneissic headlands) to smaller scale, such as resistant basaltic bodies (*e.g.*, dykes, or valley fills). The emphasis here is that, following the post-glacial transgression, coastal erosion has removed more easily eroded material that formerly had enveloped a geological feature (or landform) on the hinterland, and has isolated that feature now making it a prominent *coastal* landform. The landform and its coastal morphology has not formed primarily as a result of marine inundation, as is the case for a ria coast, or formed as a result of erosion of a geologically relatively uniform system, as is the case of the sea cliff along the edge of the Nullarbor Plain, but is the result of the exposure by coastal erosion of a geologically harder "node". In Western Australia, examples of coasts formed by exhuming or isolation of older landforms are: 1. rounded coastal granitic headlands (formerly inselbergs, or monadnocks that were scattered and partly to fully buried by Tertiary sediments inland of the Esperance coast) now exposed by the erosion of the surrounding Tertiary sediments; and 2. the outcrop of Bunbury Basalt, south of Bunbury, with outcrop of basalt-filled valley tract now exposed by the erosion of the enclosing Cainozoic sediments.

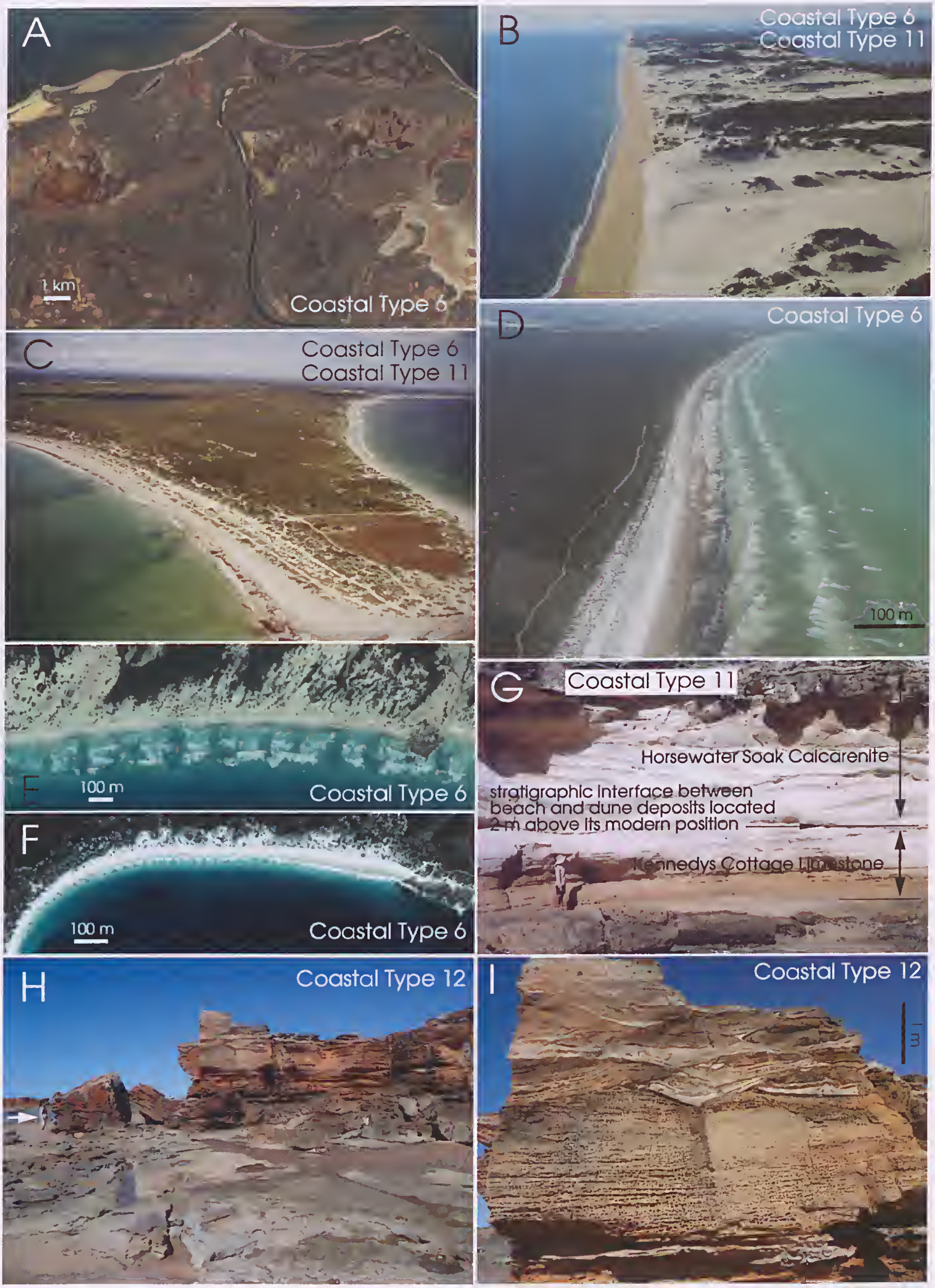
Coastal Type 4 can be assigned to the following two geoheritage categories: *modern, active landscapes* in that they have been formed by the post-glacial marine inundation of the pre-transgression landscape and its subsequent erosion. Where such coastal landforms have been in existence since the early to middle Holocene, and are now largely relict from earlier Holocene time, they represent a coastal type that can be assigned to the geoheritage category of *geohistorical sites* where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed. However, more generally, though mostly an exhumed feature, these coastal types carry a degree of on-going processes such as erosion.

Type 5: coasts developed by marine inundation *and* sedimentary infilling

Coastal landforms developed by marine inundation of the bedrock geology, or hinterland landforms *and* sedimentary infilling of the inundated bays, gulfs, or lagoons may vary in size from large-scale (such as sediment-filled gulfs) to medium-scale features such as sediment-filled swales in Holocene-inundated Pleistocene limestone-barrier complexes. Coastal sediments filling inundated regions/areas can wholly fill the marine embayments, or only partially fill them. Examples include the seagrass bank sediment-filled linear embayments that have shoaled to tidal levels in the Edel Land system of Shark Bay (*e.g.*, Useless Inlet, Boat Haven Inlet, Depuch Inlet), the tidal-sediment, partial fill fringing the gulf of King Sound, and the tidal-sediment fill between the barrier-island complex of Pleistocene limestone at Salmon Inlet (west of Port Hedland). The emphasis here is that coastal sedimentation has modified the morphology of the coast after the initial post-glacial marine inundation by sedimentary infill or partial infill, resulting in varying coastal forms from large scale to medium scale.

Some of the sedimentation in this type of coast is the result of marine erosion acting on the inundated coast. The Peron Peninsula at Shark Bay is an example: marine transgression after the last glacial period has inundated the ancestral "gulfs" of Shark Bay, leaving the ridge of red sand as a peninsula, and coastal erosion has developed sandy shorelines, recurved spits, sand platforms, and (calcrete) breccia ribbons.

◄ Figure 8. Coastal forms in Western Australia. A. Ria coast in the Kimberley Region (Coastal Type 1). B. Partly sediment-infilled ria coast in the Kimberley Region (Coastal Type 2). C. Partly sediment-infilled limestone barrier coast in the Pilbara Coast (Coastal Type 5). D. Limestone barrier coast in the Pilbara Coast with sediment infilling the inter-ridge swales (Coastal Type 5). E. Wholly erosional coast, the Baxter Cliffs along the edge of the Nullarbor Plains (Coastal Type 3). F. Coast formed by exhuming of inselbergs in the Esperance region (Coastal Type 4). Inselbergs on the coastal plain, still partly buried by Tertiary sediments, are visible in the background. G. Coast formed by exhuming of a valley-fill of Mesozoic basalt (the Bunbury Basalt) south of Bunbury (Coastal Type 4). H. Coast comprised of sedimentary deposits (shoaled tidal-flat sediments), with superimposed erosional features, *viz.*, tidal creeks (Coastal Type 7).


A
1 km
Coastal Type 6
B
Coastal Type 6
Coastal Type 11
C
Coastal Type 6
Coastal Type 11
D
Coastal Type 6
100 m
E
100 m
Coastal Type 6
F
100 m
Coastal Type 6
G
Coastal Type 11
Horsewater Soak Calcarenite
stratigraphic interface between beach and dune deposits located 2 m above its modern position
Kennedys Cottage Limestone
H
Coastal Type 12
I
Coastal Type 12
1 m

Coastal Type 5 can be assigned to the following two geoheritage categories of *modern, active landscapes* in that coastal landforms developed by the post-glacial marine inundation of the landscape, and their sedimentary infilling, if still on-going, is extant. Where Holocene sedimentation is now inactive, the coastal type can be assigned to the geoheritage category of *geohistorical sites* where the history of the Earth can be reconstructed, or the processes within the Earth in the past (in the Holocene) can be reconstructed.

Type 6: landforms wholly constructed by Holocene coastal processes

This type of coast comprises landforms wholly constructed by sedimentary coastal processes that have been active during the Holocene. This Coastal Type focuses on coastal landforms, not on sedimentary sequence. Examples at the large and medium scale include dune barriers, beach-ridge systems, beach/dune systems, estuarine sedimentary accumulations, and deltas, amongst others. These tend to be relatively permanent coastal landform features. Examples at the small scale include sand spits, coquina (shell) spits, emergent tidal deltas, ridge-and-runnel complexes, and beach cusps, amongst others. Some of the smaller-scale rhythmic coastal features tend to be relatively short term features (*e.g.*, ridge-and-runnel complexes, and beach cusps), although for some coasts, because of local coastal morphology such as headlands flanking curved beaches, combined with prevailing wave and wind patterns, there may be a tendency for some rhythmic coastal forms to be recurring on a regular basis. Examples of significant large- and medium-scale coastal landforms in Western Australia wholly constructed by coastal processes include the coastal carbonate mud flats, sandy barriers, and earlier Holocene barriers of the Canning Coast (Semeniuk 2008), the deltas and barriers of the Pilbara Coast (Semeniuk 1996a), the delta of the Gascoyne River (Johnson 1982), the twin cuspate foreland of the Rockingham-Becher area (Searle *et al.* 1988), and the Leschenault Peninsula Barrier Dune system (Semeniuk 1985b).

Coastal Type 6 can be assigned to the geoheritage category of *modern, active landscapes* in that coastal landform development is extant.

Type 7: landforms constructed by Holocene coastal sedimentary processes that have superimposed erosional features

This type of coast comprises landforms constructed by Holocene sedimentary coastal processes but where there has been later erosion. Thus it comprises depositional forms, with superimposed erosional landforms. This Coastal Type also focuses on coastal landforms, not on sedimentary sequences. Examples at the large and medium scale include tidal flats with tidal-creek erosion, dune barriers with an eroding seaward margin, and beach-ridge systems with an eroding seaward edge, amongst others. Examples in Western Australia of such coastal landforms initially constructed by Holocene coastal processes but with subsequent superimposed erosion include tidal creeks cut into tidal flats in King Sound, Roebuck Plains, and Port Hedland (Semeniuk 1981a, Semeniuk 2008), the eroding seaward edge of some deltas of the Pilbara Coast (Semeniuk 1996a), and the eroding tip of Point Becher of the Rockingham-Becher area (Semeniuk 1995).

Coastal Type 7 can be assigned to the geoheritage category of *modern, active landscapes* in that coastal landform development is extant.

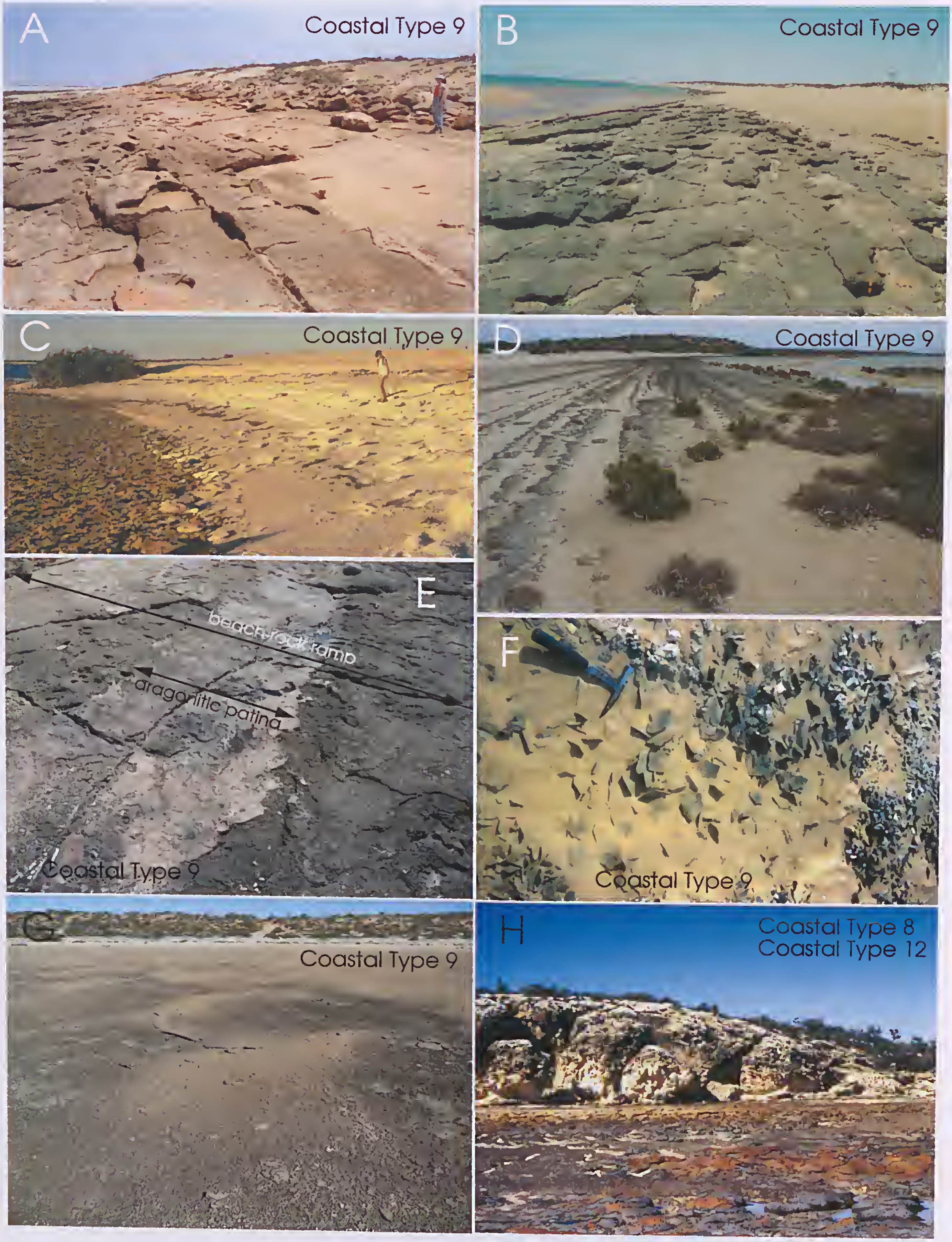
Type 8: biogenic coasts

Coasts can be built by biogenic processes. This refers to coasts that have developed hard-surface reefs (coral reefs, serpulid reefs, oyster reefs, stromatolitic reefs) which are not due to sedimentary deposits that merely have a skeletal component. Skeletons of organisms behave as sediment particles under action of waves, tides, currents and wind: they are transported, sorted, built accumulations, and develop sedimentary structures. As such, though biogenic in origin, skeletal accumulations are treated as sediments in this paper.

Biogenic coasts tend to range from microscale to the mesoscale. They are locally developed in Western Australia, *e.g.*, where oysters form thick crusts or reef-like accumulations on cliff shores (as in the Dampier Archipelago), or where coral reefs fringe shallow subtidal to low tidal rocks and rock platforms (*e.g.*, Port Hedland tidal platforms). In Shark Bay, stromatolitic reefs form in the tidal zone (Logan *et al.* 1974), developing resistant structures fronting Hamelin Pool and prograding seawards (Figure 10H). Biogenic coasts most commonly occur in combination with other coastal forms (Figure 10H), *i.e.*, as zones or patches or short sectors within erosional or sedimentary coasts, and only infrequently in Western Australia dominate the coast.

Coastal Type 8 can be assigned to the geoheritage categories: *modern, active landscapes* in that the processes and products are extant and (if stranded and fossil) as *geohistorical sites* where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed because there is an emphasis on the record of sedimentary history, ocean history, climate history and sea-level history. The elevated stromatolitic reefs of Shark Bay illustrate the use of these structures to infer former higher Holocene sea levels.

◀ **Figure 9.** Coastal forms in Western Australia. A. Coast formed wholly by sedimentation – a large delta, *viz.*, the Ashburton River delta, Pilbara Coast (Coastal Type 6). B. Coast formed wholly by sedimentation – a barrier dune system, *viz.*, the Leschenault Peninsula (Coastal Types 6 and 11). C. Coast formed wholly by sedimentation – a cuspate foreland, *viz.*, Point Becher cuspate foreland (Coastal Types 6 and 11). D. Coastal form developed by modern processes, *viz.*, ridge-and-runnel complex east of Esperance (Coastal Type 6). E. Coastal form developed by modern processes, *viz.*, rips and their feeder channels in the Esperance area (Coastal Type 6). F. Coastal form developed by modern processes, *viz.*, beach cusps in the Esperance area (Coastal Type 6). G. Cliff cut into Holocene limestone at Port Smith (Canning Coast) showing stratigraphic interface between the beach facies and dune facies located some 2 m above their modern position (Coastal Type 11). H. Cliff cut into the Broome Sandstone in the Entrance Point area (Broome) showing well-exposed stratigraphy, structures and lithology (Coastal Type 12); person for scale. I. Close-up of cliff shown in (H) showing details of sedimentary structures, cut-and-fill structure, sedimentary sequence, and well-exposed lithologies (Coastal Type 12). Tafoni are also evident in the lower part of the photograph.


A
Coastal Type 9
B
Coastal Type 9
C
Coastal Type 9
D
Coastal Type 9
E
beachrock ramp
aragonitic patina
Coastal Type 9
F
Coastal Type 9
G
Coastal Type 9
H
Coastal Type 8
Coastal Type 12

Type 9: coasts with dominant or conspicuous diagenetic features

Diagenesis involves precipitation, solution, or chemical/mineral reactions. Diagenetic features can be formed along the coastal zone by hydrochemical, biological, and physical processes, acting alone or in combination in response to the interactions of seawater, fresh water, and evaporation and transpiration gradients across the tidal zone. The products may be fine-scale and small-scale and isolated, but conspicuous, overprinting existing sediments and rocks and superimposed on any of the Coastal Types described above, or can come to dominate the coast as medium-scale products, and locally, diagenites, as in massive beach-rock occurrences that form "rocky shores" (Figure 8 of Semeniuk 2008) and in extensive cemented pavements and breccia pavements. Examples of diagenetic coasts include beach rock (Ginsburg 1953) and gypsum precipitates such as nodules, crystal rosettes, crusts, and crystals forming an interlocking resistant meshwork, under hypersaline flats (*cf.* Logan 1974; Shinn 1983).

Diagenetic features and sequences of significance in Western Australia include those recorded by Logan (1974) in Shark Bay (*viz.*, carbonate-cemented crusts, gypsum precipitates, beach rock), those of the Pilbara Coast (Semeniuk 1996a), and beach rock of the Canning Coast (Semeniuk 2008). Figures 10A–10G illustrate beach-rock ramps forming seafronts along the Canning Coast and Pilbara Coast, a cemented upper beach surface, carbonate pavements, cemented carbonate layers, and a meshwork of gypsum rosettes from a supratidal flat all in Shark Bay, and an aragonitic patina (crust) formed on beach rock along the Canning Coast.

Coastal Type 9 can be assigned to the geoheritage category of *modern, active landscapes* in that the processes and products are extant.

The importance and implications of coasts formed by diagenesis or strongly overprinted by diagenesis will be explored in more detail in the Discussion.

Type 10: erosional coasts recording sea-level history

This is a type of coast where erosion manifests specific detailed Holocene Earth-history information through the expression of geomorphic features preserved along the shore. Contrasting with accretionary coasts where sea-level history can be preserved (see below), erosional coasts, where there has been cutting of platforms or pavements in the intertidal zone, can record coastal history, and in particular sea-level history (again, with relative sea-level history being eustatic, or the result of tectonism). Rocky shore sedimentary deposits and biogenic imprints also may be preserved. In this type of coast, there is focus on environmentally-specific erosional features (that can be related to mean sea level, or a tidal level). This is exemplified by various platforms, benches, and pavements cut into calcarenite exposed at the coast along south-western Australia, along the Pilbara Coast, and along the Canning Coast. Examples of erosional coasts that have been used to construct (eustatic or tectonic) sea-level history include rocky shores cut into calcarenite at Point Peron (Fairbridge 1950) and Rottnest Island (Playford 1988).

Coastal Type 10 can be assigned to the geoheritage category of *geohistorical sites* where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed because there is an emphasis on the record of sea-level history.

Type 11: depositional coasts recording tectonic history, sedimentary history, ocean history, climate history and sea-level history

This is a type of coast where sedimentation has stratigraphically recorded specific Earth-history information. Sedimentary sequences can record sedimentary history, oceanic history, climate history and sea-level history (a geohistorical record). This Coastal Type thus focuses on stratigraphy and the fine- to small-scale sedimentary sequences for reconstructing geohistory in the Holocene. Examples in Western Australia of coastal sedimentary packages that record sedimentary history, climate, sea-level history (with relative sea-level history being eustatic, or the result of tectonism), and ocean history are provided by the Leschenault Peninsula Barrier Dunes (Semeniuk 1985b), the cuspate forelands of the Rockingham-Becher to Whitfords area (Semeniuk & Searle 1986; Searle *et al.* 1988), the Preston Beach area (Semeniuk 1996b), and the Canning Coast (Semeniuk 2008; and Figure 9G). The sedimentary sequences containing the geohistorical records may not necessarily be large to the extent that they dominate the landform, as are the examples cited above, nonetheless they can still contain valuable information.

Coastal Type 11 can be assigned to the geoheritage category of *geohistorical sites* where the history of the Earth or its past processes can be reconstructed, because there is an emphasis on the record of sedimentary history, ocean history, climate history and sea-level history.

Type 12: sea cliffs exposing lithology, stratigraphy, contacts, and structures

Sea cliffs are recognised as special sites of potential geoheritage significance, providing exposure of stratigraphic sequences, igneous and metamorphic sequences and contacts and structures; types sections,

◀ Figure 10. Coastal forms developed by diagenesis and biogenesis in Western Australia. A. Tidal beach-rock ramp in northern Canning Coast (Coastal Type 9). B. Tidal beach-rock ramp in the Dampier area, Pilbara Coast (Coastal Type 9). C. High tidal cementation indurating the upper surface of shell beach in Shark Bay, with break-up of cemented crusts to form rock slabs (Coastal Type 9). D. High-tidal surface of truncated seaward-dipping sediment layers that have been cemented in bands, resulting in a coast in Shark Bay with exposure of alternating indurated and semi-indurated layers (Coastal Type 9). E. Patina of a thin aragonite crust on a beach-rock ramp at Broome (Coastal Type 9). F. Rosettes of gypsum blades, in an interlocking resistant meshwork, forming a sheet on and under the supratidal flat, Shark Bay (Coastal Type 9). G. Cemented pavement in the high-tidal zone in eastern L'Haridon Bight, Shark Bay (Coastal Type 9). H. Stromatolitic reef in middle ground and foreground, comprised of stromatolite heads and indurated sheets (Coastal Type 8); in background, cliff cut into Pleistocene Carbla Oolite (Coastal Type 12) at its type section at Goat Point.

reference sections, or culturally significant sites, *i.e.*, significant features of bedrock are made more evident by coastal erosion and provide the opportunity to study Earth history in detail. With such diverse reasons for their geoheritage significance, cliffs do not fall into the gradation of natural groups as do the other coasts, and is essentially an *ad hoc* allocation with an emphasis on geological content, not coastal geomorphology. While this coastal form is described as "sea cliff" it must be stressed that this landform can vary from vertical cliffs to steeply plunging shores. The main feature is that marine erosion exposes critical geological content, which may be manifest in vertical cliffs or in steeply plunging coastlines.

While similar geological features may be exposed in inland cliff faces, river banks, soil-covered hill sides, or local outcrops, commonly there are better and more extensively wave-washed natural exposures along the coast as a result of cliff erosion, washing by wave action, erosion by wave action, and salt weathering (Brocx & Semeniuk 2009). This also is evident in the literature because some of the best and classic stratigraphic locations and geological features are manifest in sea cliffs: the Devonian sequences around the coast of Devonshire in south-western England (Rudwick 1985), the chalk cliffs of Beachy Head, Seaford Head and the Seven Sisters along southern England (Gallois 1965; Melville & Freshney 1982), the Old Red Sandstone along the Orkney Islands in Scotland, the unconformity at Siccar Point in Scotland (Barclay *et al.* 2005; Brocx & Semeniuk 2007), the wave-cut platform developed on steeply-dipping layered limestone along the Bay of St. Jean-de-Luz, France (Machatschek 1969), the unconformable contact between Precambrian rocks and Permian glacigene sediments at Hallett Cove in South Australia (Parkin 1969; Dexel & Preiss 1995), and the Miocene limestone in the Port Campbell area ("The Twelve Apostles") in Victoria (Birch 2003). A review of texts dealing with Nature Reserves and coasts also shows that exposures of stratigraphic sequences and geological features are best manifest in sea cliffs (Bennett 1989; Blandin 1992; Goudie & Gardner 1985; Holmes 1966; Michel 1991; Sale *et al.* 1989; Snead 1982; Soper 1984).

Often sea-cliff exposures may expose extensive bedding-plane features, and lithologically-determined structural benches not as well evident in inland outcrops. For instance, shales that are recessively weathering in inland outcrops and cliffs, may exhibit sedimentary and palaeontological features on the bedding plane as a result of marine erosion, thus exposing important aspects of lithology, sedimentary structures, and palaeontology.

Examples of cliffs of significance in Western Australia include: exposures of Precambrian igneous rock in the Dampier Archipelago (Figure 13 in Semeniuk 1986), the granitoid/gabbro contact at Hearsons Cove (Figure 6.4 in Brocx 2008), Precambrian exposures at Sugarloaf Rock, Skippy Rock, Barge Bay and Ringbolt Bay along the Leeuwin-Naturaliste Ridge (Myers 1994), Precambrian gneiss, granite, and migmatite at The Gap, near Albany, Precambrian granite with xenoliths of earlier granite, west of Esperance (Figure 18 in Myers 1997), the Silurian Tumblagooda Sandstone at Red Bluff, Kalbarri (Figure 1C in Brocx & Semeniuk 2009); the Mesozoic Broome Sandstone at Gantheaume Point and Entrance Point at Broome (Figure 9H and 9I); exposure of columnar-jointed Bunbury Basalt at Black Point (Figure 41 in Playford *et al.* 1976); the Tertiary Toolinna Limestone, Wilson Bluff Limestone, and Abrakurrie Limestone at the edge of the Nullarbor Plain (Figure 70 in Geological Survey of Western Australia 1975, and Figure 4–19B in Geological Survey of Western Australia 1990); the Quaternary Tamala Limestone of the Zuytdorp Cliffs (Figure 36 in Geological Survey of Western Australia 1975); Pleistocene aeolianite and soil sheets at Hamelin Bay; and Precambrian rock, an elevated Precambrian/Pleistocene unconformity, Pleistocene aeolianite, marine bands, shore platform, and exhumed karst at Bunker Bay (in Fairbridge & Teichert 1952).

Coastal Type 12 can be assigned to the following three geoheritage categories: *type locations for stratigraphy*, fossils, and mineral sites, including locations for teaching, research, and reference; *cultural sites* where classic locations have been described; and *geohistorical sites* where there are classic exposures in cliffs and outcrops where the history of the Earth can be reconstructed, or the processes within the Earth in the past can be reconstructed.

In Western Australia, stratigraphic type sections that are located and well exposed as sea cliffs at the coast are: the Broome Sandstone at Gantheaume Point (Brunnschweiler 1957), the Toolinna Limestone at Toolinna Cove (Lowry 1968), the Peron Sandstone, at Cape Peron, Shark Bay (Logan *et al.* 1970), the Tamala Limestone at Zuytdorp Cliffs (Geological Survey of Western Australia 1975, amended from Tamala Eolianite of Logan *et al.* 1970), the Pleistocene Carbla Oolite at Goat Point (Logan *et al.* 1970; and Figure 10H), and the Holocene Kennedy Cottage Limestone and Horsewater Soak Calcarenite along the shores of Willie Creek (Semeniuk 2008).

Level 3 – fine-scale refinement of Coastal Types and coastal products

Environment-specific features mentioned earlier in the review of other coastal classifications can be identified, described and comparatively assessed within the setting of the twelve coastal categories. For instance, an erosional coast may be assigned geoheritage significance based on its local geology or bedrock exposure, its representativeness, or on some local feature not found elsewhere, *e.g.*, the Tertiary limestone along the Baxter Cliffs in Western Australia stands separate to the unconformity exposed at Hallet Cove in South Australia to the Permo-Triassic sequences along the southern and central cliff coast of New South Wales, and to the Cretaceous chalk cliffs in Sussex, England. While all these sites illustrate examples of sea cliffs, each provides its own level of international and national significance based on geological (and tectonic) setting, age of sequence, stratigraphic sequence, and specific local (unique) feature.

The full extent of further subdivision of Coastal Types for assessing geoheritage significance, in developing an inventory of coastal features particular to geological and environmental setting, will be dependent on the variability in geology (including tectonism), geomorphology, diagenesis, climate and oceanography that is manifest locally, and is outside the scope of this paper. It is not possible in this paper to identify every nuance of coastal variation in Western Australia (or globally) for purposes of assessing geoheritage significance comparatively, rather, we illustrate the approach to fine-scale subdivision of the main Coastal Types. Table 3 lists some examples of the finer-scale features for selected coastal regions in Western Australia.

An inventory of the key geological features for eleven coastal sites in Western Australia is presented in Table 4. The sites are selected to illustrate coasts in various geological, climatic and oceanographic settings, to illustrate a contrast in detail and significance of cliff types cut into Silurian, Mesozoic, or Quaternary rocks, and to contrast the detail between some sedimentary coasts. Information from such an inventory provides a basis for inter-regional to international comparison of coastal types for determining their representativeness or unique nature for purposes of assessing geoheritage significance and for geoconservation. For instance, although the Point Becher cuspate foreland and the Leschenault Peninsula barrier dunes, both in the Perth Basin region, are Coastal Type 6, they represent different styles of sedimentary accumulations, with a different set of finer-scale coastal landforms and sedimentary structures. Again, for other coasts developed by modern sedimentation (Type 6 coasts), but from different coastal regions, Table 4 contrasts a wave-dominated delta in the Pilbara region (the Maitland River delta) and another in the Carnarvon Basin region (the Gascoyne River delta). Though wave dominated, one is macrotidal and the other microtidal, and there is a difference in finer-scale geomorphic and sedimentary features within each in terms of specific landforms developed, and smaller-scale sedimentary structures, which render them different. Thus, regional geological, climate and oceanographic settings of a coast will result in site-specific expressions of climate history (*e.g.*, expressed in sediments through fauna, microbiota such as foraminifera, and diagenesis), history of storminess (*e.g.*, expressed in cheniers and tempestites), and MSL history (expressed in heights of stratigraphic interfaces, or sea-level specific landforms), amongst others. Table 4 also specifically contrasts coastal products at the fine scale of the sea cliffs using one cut into Silurian sandstone at Red Bluff and another cut into Mesozoic sandstone at Gantheaume Point.

This approach to identifying finer-scale coastal features for determining geoheritage significance, as outlined in Tables 3 and 4, can be systematically applied to other coasts elsewhere State-wide, Nationally and

Table 3

Examples in Western Australia of finer-scale features occurring within Level 2 Coastal Types

Level 2 Coastal Type	Potential finer-scale features for a given Coastal Type, and next stage of coastal division
Type 1: landforms developed by inundation	coasts such as ria, dendritic embayed forms, ridges-and-gulfs, or limestone barrier islands (all based on the inundated ancestral hinterland morphology)
Type 2: coast developed by inundation *and* erosion	coasts as for Type 1, as to form, with erosion features such as cliffs, talus, shore platforms and benches, notches, micro-pinnacles and tafoni, and lithology-related variation in style of erosion (*viz.*, rounded shores, plunging cliffs, stepped platforms and benches, serrated platforms, high-tidal pavements) linked to oceanographic and climate setting
Type 3: coast developed wholly by erosion	cliffs, shore platforms and benches, notches, micro-pinnacles and tafoni, lithology-related variation in style of erosion (rounded shores, plunging cliffs, stepped platforms and benches, serrated platforms, high-tidal pavements) linked to oceanographic and climate setting
Type 4: coasts developed by exhumation of older landforms	isolated headlands, coastal knolls, cove-and-headland morphology, and the erosional products peripheral to the resistant landforms
Type 5: coast developed by inundation *and* sedimentation	ria, dendritic embayed coasts, ridges-and-gulfs, or limestone barrier islands with associated depositional forms such as barriers, spits, tidal flats, beach-ridges, bay-head deltas, linked to oceanographic and climate setting
Type 6: coast constructed by sedimentation	barrier dunes, cuspate forelands, beach-ridge plains, beach/dune coasts, deltas, prograded tidal flats
Type 7: coast constructed by sedimentation; superimposed erosion	tidal creek, or seafront erosion of deltas and prograded tidal flats; and eroding (cliffed) seafront of barrier dunes, cuspate forelands, and beach-ridges, with style of erosion linked to oceanographic and climate setting
Type 8: biogenic coasts	bioherms or biostromes constructed by corals, oysters, mussels, stromatolites, serpulid worms, mainly in relationship to climate
Type 9; diagenetic coast	coasts are comprised of beach-rock, cemented pavements, gypsum pavement, linked to oceanographic and climate setting
Type 10: erosional coasts recording Holocene history	identifying sea-level related erosional features, or elevated diagenetic and biogenetic features on the rocky shore
Type 11: depositional coasts recording Holocene history	identifying type of stratigraphy and biostratigraphy, and identification of sea-level, climate, and ocean-history features related stratigraphy
Type 12: sea cliffs exhibiting lithology and history	identifying geological Formation, and rock sequences and rock features exposed by cliffs; details deriving from, and dependant on Level 1 setting

Table 4

Some finer-scale features occurring along selected sites of coastal geoheritage significance in Western Australia

Location	Geological, climatic, oceanographic setting	Coastal Type	Key smaller-scale features at the site of geoheritage significance
Willie Creek, north of Broome	northern Canning Basin Coast: Tropical semiarid climate; wave- and tide-dominated macrotidal regime	Type 7 and Type 11	cliff cut into Holocene shoaling tidal sand flat, beach, and dune deposits now lithified to limestone (Willie Creek Calcarenite, Kennedy Cottage Limestone, Horsewater Soak Calcarenite; Semeniuk 2008); type location for the Willie Creek Calcarenite, Kennedy Cottage Limestone, and Horsewater Soak Calcarenite; oolitic limestone; earlier Holocene bouldery tempestite deposits in the limestone; earlier Holocene bubble and other beach sedimentary structures; sea-level history; rocky shore cut into Holocene limestone; beach rock exposures; erosion by tidal creeks; ridge-and-runnel coastal forms (Semeniuk 2008)
Gantheaume Point, Broome	northern Canning Basin Coast: Tropical semiarid climate; wave- and tide-dominated macrotidal regime	Type 10 and Type 12	Mesozoic sandstone (Broome Sandstone) exposed in high cliffs in a wave-dominated and macrotidal setting; exposure of platforms, tessellated pavements, ramps, notches, benches, boulder talus, tafoni; type location for the Broome Sandstone; exposure of details of sedimentary lithology and structures, such as cut-and-fill and channel forms, cross-bedding in sandstone, conglomerate, mud layers, mud cracks, burrows, and mud flake breccia, unconformably overlain by Mowanjum Sand (Semeniuk 2008) with fissures filled with red muddy sand; breccia and soil developed between Broome Sandstone and Mowanjum Sand; decimetre-sized polygonal cracking and fissure-fills on the surface of the Mowanjum Sand
Finucane Island, Port Hedland	Pilbara Coast: this area consists of local outcrops of Precambrian rocks (islands), and coastal fringing Quaternary sedimentary deposits; Tropical arid climate; wave- and tide-dominated macrotidal regime	Type 5 and Type 10	Pleistocene oolitic limestone forming a shore-parallel barrier (Semeniuk 1996a); limestone exposed in moderately high cliffs in a wave-dominated and macrotidal oceanographic setting; exposure of platforms, benches, tafoni; exposure of details of sedimentary lithology and structures in the limestone, including a Pleistocene unconformity and Pleistocene shoreline boulder deposit, unconformably overlain by Holocene shell gravel and dune sand with fissures filled with shell and sand (Semeniuk 1996a); sea-level history
Hearson Cove, Dampier Archipelago	Pilbara Coast: this area consists of outcrops of Precambrian rocks (islands) sheltering Quaternary sediment-filled embayments; Tropical arid climate; wave- and tide-dominated macrotidal regime	Type 5 and Type 12	Precambrian igneous rock contact between intrusive gabbro/dolerite sill and country rock granite; lithological and grain-size layering in the gabbro/dolerite; lithological variation in the gabbro/dolerite; extremely coarse pyroxene crystals in the gabbro towards its base; granophyre textures in the granitoid as a result of the gabbro/dolerite intrusion; inundated (formerly terrestrial, hill-flanking) boulder deposits now forming a bouldery shore; Hearson Cove is the seaward edge of a prograded, sediment-filled former strait; high-level, mid-Holocene cementation of the boulder deposit (essentially a bouldery "beach-rock"); modern beach rock locally occurring along the Hearson Cove beach; extremes of facies variation within Hearson Cove (gravel grading to fine sand to muddy sand in response to graded wave energy); geomorphic sedimentologic nature of the shore; reflective beach and dissipative sand flats, and recurring beach cusps formed in shell gravel and in various grades of sand
Maitland River delta, Dampier Archipelago region	Pilbara Coast: this area consists of outcrops of Precambrian rocks (islands) sheltering Quaternary sediment-filled embayments; Tropical arid climate; wave- and tide-dominated macrotidal regime	Type 6 and Type 11	wave-dominated macrotidal delta, comprised of prograded (seaward) sand ridges, mud- and sand-floored inter-ridge lagoons, sandy cheniers, and mud-floored tidal flats, with the mid- to high-tidal, mud-and-sand sequence shoaling from sandy and shelly sand low-tidal flat sediments (Semeniuk 1996a); mangrove facies in mid- to high-tidal zone; muddy sediments, mangrove facies; and low-tidal sandy sediments are mostly bioturbated; surface structures at fine scale comprised of sand ripples, mud cracks, mud flakes, and burrow punctures

Goat Point, Shark Bay	Carnarvon Basin coast: this location is within the ridge-and-gulf complex of Shark Bay; Subtropical arid climate, wave-dominated microtidal regime	Type 8 and Type 12	sea cliff cut into an aeolian mound of Pleistocene oolitic limestone (Carbla Oolite); type location for the Carbla Oolite (Logan *et al.* 1970); cliff shows aeolian cross-layering, and a Pleistocene shoreline breccia; the coast is also biogenic in the tidal zone, and comprised of stromatolitic reefs
Gascoyne River delta	Carnarvon Basin coast: this location is to the north of the ridge- and-gulf complex of Shark Bay; Subtropical arid climate, wave-dominated in a microtidal regime	Type 6 and Type 11	wave-dominated microtidal delta, asymmetric because of strong southerly winds, comprised of prograded repetitive sand ridges, mud- and sand-floored inter-ridge lagoons, with mangrove facies in the mud-floored lagoons, shoaling from a sandy mid- to low-tidal flat beach and bar (Johnson 1982); the wave-dominated, low-tidal sandy beach and bar sediments are laminated and cross-laminated, wind-dominated supratidal dune (sand ridge) sediments are large-scale cross-laminated; protected and biogenically-altered mid- to high-tidal sediments are mostly bioturbated; surface structures at fine scale comprised of sand megaripples, sand ripples, shell pavements, mud cracks, mud flakes, and burrow punctures
Red Bluff, Kalbarri	Carnarvon Basin Coast: here consisting of local outcrops of Silurian sandstone, Pleistocene limestone amid Holocene deposits; Subtropical semiarid climate; wave-dominated microtidal regime	Type 2 and Type 12	Silurian sandstone exposed in high cliff in wave-dominated and microtidal oceanographic setting; rocky shore of platforms, benches, notches, ramos, boulder talus, tafoni; cliff exposures of sedimentary lithology and structures, such as cut-and-fill and channel forms, cross-bedding, cross-bedding in sandstone, conglomerate, mud layers, mud cracks, vertical burrows, animal tracks, mud-flake conglomerate and breccia, slump structures and other deformation structures (convolute bedding); unconformably overlain by Quaternary deposits such as yellow sand and aeolian calcarenite
Muderup Rocks, Cottesloe	Perth Basin Coast: here consisting of local outcrops of Pleistocene limestone and Holocene deposits; Subtropical semiarid climate; wave-dominated microtidal regime	Type 3 and Type 12	rocky shore cut into Pleistocene limestone showing former Pleistocene rocky shore unconformably overlain by a Pleistocene beach-to-dune sequence (Semeniuk & Johnson 1985); modern rocky shore showing classic geomorphic sequence of rim, platform, overhangs, cliff and notch, benches, pools, lapiés, talus breccia, and gravelly deposits; earlier Pleistocene rocky shore features of potholes, overhangs, shell gravel, lithophagic borings, echinoid excavations, bouldery deposits; one bench is an exhumed Pleistocene rocky platform; Pleistocene beach/dune stratigraphy shows shoaling-upward sedimentary sequence, with beach to dune sedimentary structures, bubble sand, and *Sepia* and *Spirula* fossils; sequence is punctured by vertical pipes filled with yellow sand, and riddled with rhizocretions; unconformably overlain by yellow sand
Point Becher, cuspate foreland, Rockingham	Perth Basin Coast: here consisting of local outcrops of Pleistocene limestone and Holocene deposits; Subtropical subhumid climate; wave-dominated microtidal regime	Type 7 and Type 11	Holocene prograded coastal plain comprised of low beach ridges (Searle *et al.* 1988; C A Semeniuk 2007), and a variety of coastal dune forms (Semeniuk *et al.* 1989); underlain by a shoaling sequence of seagrass facies sediments, beach and dune sediments; two orders of beach ridges reflecting Double Hale Cycle influence on Indian Ocean climate, and the 250-year climatic cycle (Semeniuk 1995); Point Becher preserves a history of beach ridge accretion and erosion reflecting the 250-year climatic cycle (Semeniuk 1995); Holocene sea-level history preserved in the stratigraphic sequence (Semeniuk & Searle 1986)
Leschenault Peninsula barrier dune	Perth Basin Coast: here consisting of shore-extensive Holocene deposits; Subtropical subhumid climate; wave-dominated microtidal regime	Type 7 and Type 11	Holocene retrograding barrier dune system (Semeniuk & Meagher 1981; Semeniuk 1985b) underlain by dune sand (Safety Bay Sand) and estuarine sediments (Leschenault Formation); modern barrier illustrating staggered parabolic dune development, and its geomorphic evolution to soil-covered plain; complex Searle 1986)

Internationally. Information to construct such inventories can be obtained from numerous texts and specialised papers that deal with the smaller-scale features of igneous, metamorphic, structural, and sedimentary geology, and geomorphology (as exemplified by the illustrations of small-scale geological and geomorphic features in Davis & Reynolds 1996; Emery & Kuhn 1982; Ginsburg 1953, 1975; Guilcher 1953; Hills 1949; Kelletat 1995; Pettijohn & Potter 1964; Reineck & Singh 1980; Wilson 1982). Recently, in developing a comprehensive classification of coasts, Finkl (2004) provided an exhaustive list of features that are present along coasts that can be applied to this level of categorisation.

Discussion

The categorisation of coastal types at the three levels presented in this paper can be applied to develop an inventory of coastal features, and lead to an assessment of geological and (hence) geoheritage values. Level 1 provides a context and framework for subdivision and interpretation of the significance of coasts of different geological, climate and oceanographic regions. In Western Australia, using Precambrian rock coasts as an example, the range of geological features in the folded Precambrian system of the King Leopold Mobile Zone of the south-western Kimberley region will be different to those of the Precambrian igneous complexes of the Pilbara region and those of the Albany-Fraser Orogen along southern Western Australia. Similarly, Quaternary limestone-dominated rocky shores set in a tropical arid, macrotidal and wave-dominated setting in the Pilbara Region will exhibit different geologic and geomorphic features to rocky shores cut into Quaternary limestones of the central Perth Basin.

The classification at Level 2 is based on identifying coasts developed by processes of marine inundation, erosion, sedimentation, biological activity, and diagenesis. It identifies those coastal types that have specific geoheritage value, and can be applied at the largest scale and the finer scales of coastal expression. The classification at Level 2 is designed for use in geoheritage and geoconservation: firstly, it identifies the fundamentally *different types of coasts* that form the framework for more detailed studies; secondly, it identifies those that have specific geoheritage significance or value; and thirdly, it can be used for comparative assessment, *e.g.*, coasts of inundation forms can be compared to other inundation forms, and erosional coasts can be compared to other erosional forms, and those that illustrate Holocene history or earlier geological history can be compared to a similar category of coast elsewhere. In this context, use of the coastal categories provides a consistent approach for comparative assessments in geoconservation and geoheritage, and a systematic approach for classifying, cataloguing, and assessing sites for geoheritage purposes.

Level 2 classification deals with the intergradation between coasts by recognising the intermediate forms (*e.g.*, eroded coasts with sediment accumulations) as separate Coastal Types. The classification at Level 2 also addresses the fact that different categories of coastal features (and therefore different categories of coastal features of geoheritage significance) can occur at different scales. In application, the classification is non-scalar (the Coastal Types transcend scale). Hence there is a focus on form and type, regardless of scale and, once identified and classified, coastal features can be related to a scale by descriptors. This is not to say that particular coastal features are not related to a given scale, or do not have a tendency to occur within a specified scale range (Figure 1). Some coastal types, such as rias of the Kimberley region, and the limestone barriers of the Pilbara region, are expressed more consistently at a regional scale, while others, such as beach-rock ramps along tropical Western Australia, are expressed more consistently at local scales, but many other coastal types can be recognised within varying frames of reference. Level 2 classification also provides a context for describing, comparing and assessing sites of geoheritage significance at the finer scale within a consistent framework – thus, fine-scale coastal features are compared only within similar coastal types.

Because the classification at Level 2 is designed for geoheritage purposes, some of the categories do not correlate with existing classifications (though this is not strictly necessary). Coastal Types 1–7 form a natural gradational series (starting with a Holocene marine-inundated landscape), with a trend resulting from increasing erosion on one hand *versus* a trend resulting from increasing sedimentation on the other, and are conceptually parallel, in part, to some existing classifications (*e.g.*, Valentin 1952 and Bloom 1965). However, Coastal Types 10, 11 and 12, identified as types because they record Holocene history of sea-level changes, tectonism, oceanography, climate, or record pre-Holocene geology, are not addressed in existing coastal classifications. In summary, Coastal Types 1, 2, 3, 5, 6 and 8 are, in part, covered by some existing coastal classifications, or conceptual classification schema, but Coastal Types 4, 9, 10, 11, and 12 are not recognised in existing classifications. The reason for this, as noted earlier, is that geoheritage and geoconservation have not been the basis for developing previous coastal classifications.

Using the proposed classification, a given Coastal Type can be classified from a number of different perspectives, and therefore have different geoheritage values. Eroding rocky shores exemplify this. An eroding coast can be classified as Coastal Type 3, illustrating modern coastal forms developed in response to marine erosion, with formation of vertical cliffs, wave-cut benches, lithologically-determined benches, cementation-determined benches, talus, and various microtopography. The same sea cliff, if exhibiting geomorphic features and cementation features developed during a former higher sea level can also be categorised as Coastal Type 10. If there is significant stratigraphy, or other geological content, exposed in the wave-washed cliff, the coast may also be categorised as Coastal Type 12.

The different geomorphic aspects of the coast, and different geologic components of the coast, as well as features at different scales along a given tract of coast, may have different geoheritage significance. These matters have to be addressed in identifying sites of geoheritage significance. In Shark Bay, for example, there are numerous small-scale coastal features of geoheritage significance that are embedded in larger-scale coastal systems that, in their own right, are of geoheritage significance. Small-scale features of geoheritage significance in Shark Bay include breccia pavements, or gypsum rosettes. Large-scale features of geoheritage significance include the marine-inundated ancestral topography of ridges-and-gulfs that is a feature reflecting the tectonically-active western margin of the Carnarvon Basin. Siccar Point in Scotland provides another example: the unconformity at Siccar Point has global (cultural) geoheritage significance, but at the geological and geomorphological small scale, as a rugged coast of rocky shores cut into Silurian and Devonian rocks, with cliffs and platforms, it is a site of geoheritage regional significance occurring at the geomorphic medium scale. To be useful for studies in geoheritage, and for geoconservation, the various scales at which natural features express themselves need to be considered and noted by using a scale descriptor and assessed independently.

Classification of the coastal zone and its smaller-scale products have been reported from a number of disciplines and perspectives with the result that there is a variety of systems, and a wide range of detailed studies that categorise the large-scale and finer-scale products along the coast. Coastal geomorphologists and sedimentologists have classified/ categorised the coast globally, regionally, and locally, providing over-arching and/or theoretical schemes at one extreme, and identifying smaller-scale features of the coastal zone at the other. The over-arching classification systems and other existing coastal classifications have not been used in this paper for a number of reasons. Firstly, in a context of geoheritage and geoconservation, the conceptual models, while useful for understanding the development of coastal forms, do not provide categories of coast for empirical and comparative purposes. Secondly, coastal scientists have had different objectives, and their classifications and categories have not always been applicable across disciplines, and specifically have not been directly applicable to geoheritage and geoconservation. The approaches adopted by geomorphologists, for instance, have not always been applicable to sedimentology, and *vice versa*, and that of identifying diagenetic products has not been applicable to geomorphology, sedimentation, or to erosional coasts. From the variety of studies cited above, information useful to geoheritage and geoconservation are the categories of coastal types that have been identified to date (*e.g.*, rocky shores, delta types, barriers dunes, cuspate forelands, beach cusps), and smaller-scale products such as bedforms, sedimentary structures, and fine-scale rocky-shore features, amongst others (and these are mainly applicable at Level 3). Thus, the approaches in coastal geomorphology, sedimentology, and diagenesis have not been directly applicable to the issues of geoheritage *except at the lowest level of classification of categories* that may be used in comparative inventories, or in compiling assemblages of smaller-scale features at a given site.

Diagenesis provides a good example to illustrate the lack of communication between the various disciplines in coastal science, and how scientific categorisation of products has not been directly useful to the issues of geoheritage and geoconservation, or even coastal classification.

Researchers of modern diagenesis have categorised coastal diagenetic features, but have tended to concentrate on its specific interesting effects and have therefore focused on smaller-scale products, documenting site-specific products, and providing information useful for interpreting ancient sequences, with an emphasis on diagenetically susceptible materials, such as carbonate sediments in arid and hypersaline environments. Generally, the approaches have not presented diagenesis as a unified discipline for coastal science, and the results have not always been transferable to the other areas of coastal science. As such, information on diagenesis, scattered in the literature, does not provide a framework for coastal classifications based on diagenetic products. Coasts, in fact, generally are not classified on their diagenetic products, and those formed by diagenesis are not generally recognised as a coastal type. Rocky shores well illustrate this: diagenesis is an important process-and-product component along rocky shores, especially those cut into porous Quaternary limestone, but its role in shore development and its control of microscale and leptoscale features has not been fully explored. So while there is mention of some of the products of diagenesis, the role of diagenesis in coastal development generally is seldom considered by coastal scientists. A perusal of a range of texts dealing with coastal science sometimes will find beach rock (a product of diagenesis) listed in the index, but not diagenesis itself. The corollary is that the results of most studies on diagenesis (diagenetic processes, or products), cannot be imported into geoheritage and geoconservation. We use diagenesis in Shark Bay to further illustrate this principle.

Shark Bay is designated a World Heritage area (inscribed in 1991) and, as such, it has global, national and State-wide importance. Amongst other aspects of its natural history, Shark Bay is comparatively well researched in terms of Holocene diagenesis (Logan 1974). Paradoxically, however, diagenesis is not emphasised as a natural process that has any international or national significance, and there is a general lack of application of diagenesis to coastal geomorphology, coastal evolution and, of course, to geoheritage and geoconservation.

While diagenetic processes and products were systematically described by Logan (1974) in a stratigraphic/hydrochemical framework, and the study was relatively exhaustive, some of the globally significant and unique diagenesis in the Shark Bay area was not highlighted. The study by Logan (1974) provided neither a framework, nor results, nor global comparison which could be used for developing an understanding of coastal evolution, or for geoheritage and geoconservation. That is, the results of studying diagenesis in Shark Bay were not applied to matters of coastal geomorphology, coastal erosion, coastal evolution, or many other of the aspects of coastal sedimentation. Even comparing the results from Shark Bay to other areas globally could have formed the basis of geoheritage comparisons and assessment. These outcomes are not surprising, as the objective of the study by Logan (1974) was an inventory of Holocene diagenesis within Shark Bay *per se*, not a catalogue of diagenetic products for the purposes of comparative geoheritage and geoconservation. However, the matter of diagenesis in Shark Bay does illustrate the point that one of the most comprehensive studies undertaken of diagenesis globally cannot be readily compared with other sites elsewhere, nor can it be easily transferred to matters of geoheritage and geoconservation, except on an inventory basis, to catalogue diagenetic features that may be of geoheritage significance. This example from Shark Bay underscores that diagenesis, as a process resulting in various coastal types, and controlling and modifying coastal form, largely has been overlooked by coastal scientists.

Coasts present many products of geoheritage significance, from varying expression of landforms, to products uniquely developed in the coastal zone from the interaction of coastal processes, to sea cliffs that reveal Earth history, however coastal deposits and coasts also can uniquely record a Quaternary history of sea level, climate, and oceanic processes because they interface with oceans. Such stratigraphic and biostratigraphic sequences in Western Australia have been used to document relative sea-level changes (Semeniuk 1985b, 1996b, Semeniuk & Searle 1986, Playford 1988, Searle *et al.* 1988, Semeniuk 2008), as represented by Coastal Types 10 and 11. Encoding of climate patterns is discussed further below.

The oceans dominate the Earth's surface and act as large receptors for solar radiation, encoding climate changes in a number of ways. Though not strictly globally homogeneous (in terms of salinity, temperatures, and circulation), oceans are much less heterogenous than landmasses that can express variable geology, landscape, soils, and vegetation at regional to small scales. Consequently, terrestrial environments respond to climate changes in more complex ways than oceans. It was partly for this reason, to study Quaternary climate changes, that stratigraphers and palaeoclimatologists concentrated on cores and biostratigraphy of deep ocean basins where there was/is a degree of environmental spatial consistency. In essence, therefore, the oceans can more consistently register the effects of short-term to long-term climate changes but, with oceans being fluid and circulating, the effects of climate can be relatively rapidly dispersed and not necessarily preserved. However, the coast, being the edge of an ocean, regardless of whether it is erosional or depositional, is an important zone where oceanic patterns reflecting climate and sea-level history *can* be recorded in landforms, sediments, biota, and isotopes, and can be read, if the alphabet of the encoding is manifest as landform, stratigraphic, biostratigraphic, and isotopic signatures. In Western Australia, the Holocene sequence of the Rockingham-Becher Plain in its regularly-spaced, low-relief beach ridges (Searle *et al.* 1988) records cyclic climate changes responding to the solar Double-Hale Cycle (Semeniuk 1995). Regular beach-ridge patterns recording the solar Double-Hale Cycle also have been documented in Hudson Bay by Fairbridge & Hillaire-Marcel (1977). In effect, the coast can be the permanent receiving interface (or the register) of oceanic patterns which are driven by climate changes and sea-level changes (Semeniuk 1995). In this context, the modern coastal zone can be an important site of geoheritage significance, recording the history of the Earth in the Holocene. Sequences and landforms that record this ocean history are represented by Coastal Types 10 and 11.

While most of the Coastal Types identified in this paper form part of an inter-gradational natural group, or continuum, or are products of interacting processes, *i.e.*, Coastal Types 1–9, reflecting the balance of the five marine and coastal processes, or form another natural group recording Holocene history, *i.e.*, Coastal Types 10 and 11, sea cliffs provide an anomalous category. As an *ad hoc* category with an emphasis on geological content, not coastal geomorphology or Holocene history, they are not part of a natural continuum in Coastal Types shown in Figures 4 and 5.

Sea cliffs provide an interesting example of how a coastal feature can be viewed from different geoheritage perspectives. Viewed strictly as sea cliffs, *i.e.*, geomorphologically, such coastal features would be captured as various categories in the classification presented in this paper, *viz.*, where erosion has partly modified the coast (Coastal Type 2), or has fully modified the coast (Coastal Types 3 and 4), and in this context, the emphasis on these types of coasts is geomorphological. Different sea cliffs, composed of diverse materials, would respond variably to coastal processes, and would provide geomorphologically, geologically, and processes-oriented information useful to science and to coastal managers. Sea cliffs can also preserve ocean history and sea-level history in benches and platforms (Coastal Type 10). As mentioned earlier, Coastal Type 12, sea cliffs, emphasise geological content, not geomorphic features.

Brocx & Semeniuk (2009) pointed out that sea cliffs generally provide excellent locations for studying rock sequences (sedimentary, igneous, or metamorphic), and provide some of the best exposures of geological features of geoheritage significance. Indeed, there are numerous such examples that already have been afforded global and national recognition because of their geological or cultural importance – these include the chalk cliffs along the Sussex coast in England, the unconformity first described by Hutton exposed at Siccar Point in Scotland, cliffs along the coast of Victoria (White *et al* 2003), and at Hallett Cove in South Australia (Parkin 1969; Dexel & Preiss 1995). Fine- to small-scale rock structural features, intra-lithologic features, and various lithologic types are best brought out by coastal erosion effected by wave washing, (sand-charged) wave erosion, wind erosion, and salt weathering. A range of textbooks on sedimentary structures and other geological features from the realm of sedimentary, igneous, metamorphic rocks, and structural geology reveal that a large number of well-exposed outcrops occur in the coastal zone (*e.g.*, Pettijohn & Potter 1964). In contrast to outcrops inland or along river courses (apart from regularly river-washed steep gorges), coastal outcrops not only present wave-washed and salt-weathered exposures, but also a generally better continuity of outcrop (Brocx & Semeniuk 2009). A corollary is that coastal rock exposures are often also the best outcrops for type sections and reference locations. In Western Australia, the Broome Sandstone at Gantheaume Point, the Toolinna Limestone along the edge of the Nullarbor Plains, and the Carbla Oolite at Goat Point, Shark Bay exemplify this.

While type sections, reference sections, teaching sections, culturally important geological sites, and sites that exhibit geohistorical information are variably captured in the twelve Coastal Types, it needs to be stressed that if they are to function as important geological sites, generally they should be relatively fixed (*e.g.*, cliffs) and able to be examined and revisited as knowledge expands and new research directions are developed. Along the same lines, some of the active, dynamic coastal terrains should be relatively long term features, acting as standards and reference locations that can be examined and revisited, *e.g.*, the mobile parabolic dunes of the Leschenault Peninsula, (Semeniuk & Meagher 1981), or those of the Yeagarup Dunes along the southern coast of Western Australia. Other active coastal forms appear to be relatively temporary or ephemeral, *e.g.*, ridge-and-runnels, and beach cusps, and might not be viewed as qualifying to be assigned geoheritage significance. However, we present the argument that where rips, ridge-and-runnels, and beach cusps are regularly developed at some locations (because of the configuration and orientation of the shore, the occurrence of headlands framing a curved beach or cove, and the prevailing wave climate), they stand as important teaching and research laboratories. While they may not be strictly permanent systems, rips, ridge-and-runnels, and beach cusps may be quasi-prevailing or regularly occurring for the reasons outlined above. Hence, there are locations where they can be predicted to more regularly occur. Also, as particular types of rhythmic coastal features, they can develop coastal formations and stratigraphic sequences indicative of specific coastal conditions (*e.g.*, cut-and-fill structures, lenses of trough-bedded sand, lenses of upward-shoaling sedimentary packages, shell and coarse sand lenses, and shell-lag deposits, amongst others). As natural reference sites, classrooms, and research sites, locations with quasi-prevailing or regularly occurring rips, ridge-and-runnels and beach cusps should be considered sites of geoheritage significance within the category of sites of active coastal geological processes.

This paper does not rank the coastal features as to their significance. The recognition of the twelve types of coast with different geomorphology and geological features, and the reasons for their differentiation, provide the template for identifying geodiversity and importance of the geology of the coast, and forms the first step to identifying sites of coastal geoheritage significance. The various coastal forms and coastal features can be readily assigned to the four categories of geoheritage sites as described by Brocx & Semeniuk (2007).

The Coastal Types described in this paper can be placed into a larger context, within a national or international framework, using information on geological setting (including tectonic setting) and hinterland geomorphology, as well as climate setting and oceanographic setting. The context of the coast would influence its detailed geomorphic, sedimentological, erosional and diagenetic responses. Tectonic setting, for instance, would control the developing shore morphology, the types of hinterland geomorphology that are presented at the shore, the erosion and sedimentation rates, and the types of sediment delivered to the shore. Geological setting would determine the coastal bedrock geology, which would control the "grain of the coast", the configuration of the coast, the structural and lithological controls on coastal form, the erodability of the shore, and the types of rock sequence that might be exposed. Hinterland geomorphology, once inundated by the Holocene transgression, would determine coastal forms in terms of shapes, steepness of shore, and riverine and marine interactions. Climate setting would determine water temperatures, and coastal processes in terms of tropical humid or tropical arid conditions at one extreme, to Boreal and Arctic conditions at the other (with ice interacting with coastal deposits, or annual freezing of coastal deposits), or would influence wind direction and intensities, rainfall, run-off volumes, evaporation, style of diagenesis, and effect of biodiversity, amongst others. Oceanographic setting would determine whether the coast is swell-, wind-wave-, or tide-dominated, and the prevailing direction of wave impingement. These higher-order settings provide a framework for national and international comparisons of Coastal Types presented in this paper so that features of geoheritage significance can be systematically compared and ranked in context, but not for comparing coasts with geoheritage values at smaller scales.

The hierarchical approach to classifying coasts proposed in this paper requires all three levels to be applied to be able to fully categorise a coast for assessing geoheritage values and for geoconservation (Figure 11). Applying only Level 1, *i.e.*, placing the coast in a geological, oceanographic and climatic context, clearly does not provide enough detail for delineating coastal forms for geoheritage purposes – it would just locate the coast geologically, climatically, and oceanographically without providing critical coastal product(s) information. However, the context provided by Level 1 classification is critical to the application of Level 3.

The core of the classification is at Level 2. While the benefits of Level 2 classification include categorisation of Coastal Types and, in the context of Coastal Types 10, 11 and 12, identification of different coastal forms with geoheritage significance, on its own it does not allow for detailed comparison of coastal types. For instance, for Coastal Type 3, the different types of eroded coasts occurring along the Baxter Cliffs, the limestone rocky shores in the Carnarvon Basin, or the cliffed, igneous rocky shores in the Pilbara would not be separated. For Coastal Type 6, the different types of accretionary coasts such as cuspate forelands, beach-ridge plains, barrier dunes and deltas, similarly would not be separated. However, Level 2 classification does provide a context for the subdivision that would follow, with the application of Level 3 classification, and used in conjunction with regional setting at Level 1, it provides a solid foundation to separating coastal types and provides a basis for assessing geoheritage values.

Applying Level 3 classification in isolation, *i.e.*, documenting a given coastal site in detail, will result merely in an inventory of geomorphic and geological features. However, the importance of information at Level 3 is that it separates the various coastal types on their finer structure, characteristics, and components, and can be used comparatively in an assessment capacity for determining geoheritage values. While Level 3 involves the smallest scale of information applied, its content will depend on the larger-scale geological, oceanographic, and climate setting, and the finer-scale information will have geoheritage relevance when used in conjunction with both the regional-setting context and with Level 2 classification of the coasts.

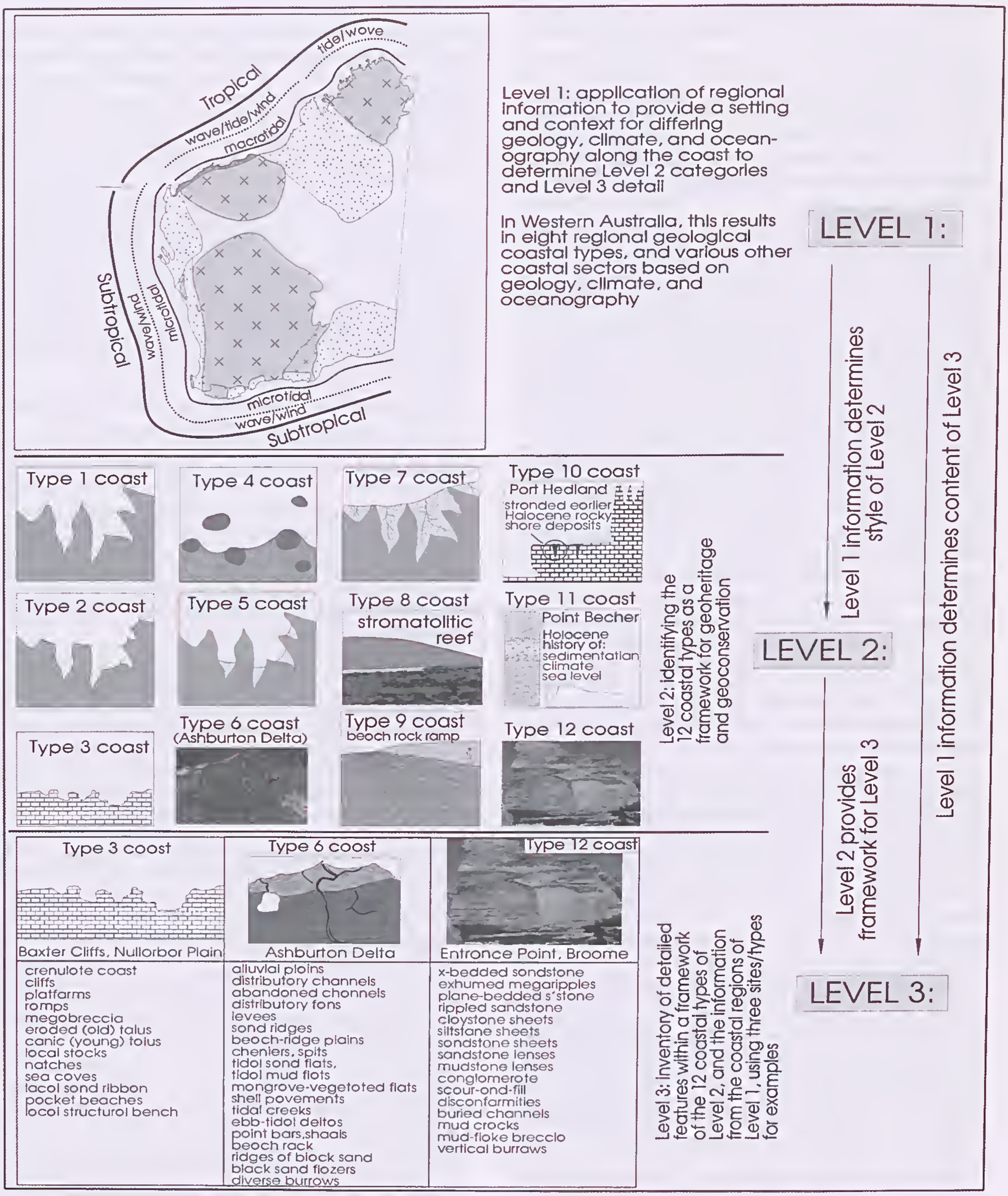


Figure 11. Application of Level 1 to Level 3 categorisation of Western Australian coasts. The three concentric lines of varying widths and styles circumferential to the coast represent, in generalised form, the extent of the tropical and subtropical coastline, the extent that a coastal sector is wave-dominated, tide-dominated, or wind-dominated, or mixed (the centrally-placed line) and, finally, the extent of macrotidal *versus* microtidal shores. Nomenclature and symbols for the cratons, orogens and basins in Western Australia are shown in Figure 3. Coastal types in Level 2 are drawn from Figures 4, 5, 9A, 9H, 10A and 10H. Coastal Type 10 at Level 2 derives from a limestone rocky shore at Port Hedland. Coastal Type 11 at Level 2 derives from the stratigraphic sequence preserved at Point Becher.

In essence, for geoconservation and assessment of geoheritage significance, all three levels of coastal classification have to be applied.

As noted earlier, classifying coastal sites for the purposes of geoheritage and geoconservation is not an easy task. In recognition of the complexity, intergradation, and variety of scales of coastal features, we have attempted to design a category-oriented (or product-oriented) classification to deal with types of coasts that can be applied to a wide variety of settings. By addressing the products developed by the five fundamental processes we believe the proposed classification at Level 2 captures the main coastal categories for purposes of assessing geoheritage significance and, as such, forms a basis for comparative assessment of sites, and a framework for a more detailed inventory as a basis for the selection of sites for geoconservation. By identifying the main coastal settings and the main processes and their combinations that develop the coastal forms and coastal products, it is possible to capture in this classification the higher-order levels of coastal categories. The classification presented herein addresses the types of coasts that are developed geomorphologically, the stratigraphic sequences that may be developed, the geohistorical record within coastal forms and coastal sequences, and the products of hydrochemical interactions – all aspects of the coast that can have geoheritage significance. Within this context, smaller-scale geological and geomorphic features can be identified for comparative purposes. But, conversely, any fine-scale features along the coast can be placed into the framework of category-oriented coastal types for inventory-based comparison and assessment to determine potential geoheritage significance.

While the approach presented in this paper is largely based on Western Australian examples, a review of the literature and site visits to locations elsewhere in Australia and overseas, show that it has potential for global applicability. Identifying geological region and climate and oceanographic setting clearly provides important information for understanding coasts, and is applicable globally. The literature already shows these underlying factors to have major influence on geological content for geoheritage purposes, as well as on coastal processes and coastal form (Davies 1980; Woodroffe 2002). At the next level, by addressing the products developed by the five fundamental processes we believe the proposed classification of twelve Coastal Types captures the main coastal categories and, as such, forms a basis for comparative assessment of sites of geoheritage significance and the selection of sites for geoconservation.

Many of the studies in coastal geomorphology, erosion, sedimentation and diagenesis have only been applicable to the issues of geoheritage and geoconservation at the specific product level (such as delta types, barrier islands, coastal dunes, as large-scale features, or ripple forms, beach cusps, flazer bedding, as small- to fine-scale features). Such coastal categories can only be applied as comparative inventories. The classification presented herein seeks to be more comprehensive and inclusive, addressing the types of coasts that are developed geomorphologically, the stratigraphic sequences that may be developed, the geohistorical record within coastal forms and coastal sequences, and the products of hydrochemical interactions – all aspects of coasts that can have geoheritage significance. In contrast to other coastal studies which describe, categorise, and classify coasts and coastal products, the classification presented here provides the basis for a systematic inventory-based assessment of coastal types and products for geoheritage and geoconservation.

Acknowledgements: For VS, this work is part of VCSRG P/L R&D Project #s 3 and 12. Page charges, costs for coloured illustrations, and other ancillary expenses for this publication were met by VCSRG P/L.

References

Allen J R L 1970 Physical processes of sedimentation. George Allen & Unwin, London.

Barclay W J, Browne M A E, McMillan A A, Pickett E A, Stone P & Wilby P R 2005 The Old Red Sandstone of Great Britain, Geological Conservation Review Series, No. 31, Joint Nature Conservation Committee, Peterborough, 393 p.

Bates R L & Jackson J A 1987 Glossary of Geology (3rd edition). American Geological Institute, Virginia.

Bennett L 1989 Britain's Nature Reserves. MacMillan, London.

Birch W D (ed) 2003 Geology of Victoria. Geological Society of Australia Special Publication 23. Geological Society of Australia (Victoria Division).

Bird E C F & Dent O F 1966 Shore platforms of the South Coast of New South Wales. Australian Geographer 19: 71–80.

Blandin P (ed) 1992 La nature en Europe: Paysages, Faune et Flore. Bordas, Paris.

Bloom A L 1965 The explanatory description of coasts. Zeitschrift fur Geomorphologie. NF 9: 422–436.

Brocx M 2008 Geoheritage – from global perspectives to local principles for conservation and planning. Western Australian Museum, Perth, Western Australia.

Brocx M & Semeniuk V 2007 Geoheritage and geoconservation – history, definition, scope and scale. Journal of the Royal Society of Western Australia 90: 53–87.

Brocx M & Semeniuk V 2009 Coastal geoheritage: encompassing physical, chemical, and biological processes, shoreline landforms and other geological features in the coastal zone. Journal of the Royal Society of Western Australia 92: 243–260.

Brunnschweiler R O 1957 The geology of the Dampier Peninsula, Western Australia. Bureau of Mineral Resources Report 13.

Coleman J M 1976 Deltas: Processes of Deposition and Model for Exploration. Continuing Education Publication Company, Champaign, Illinois.

Davies J L 1980 Geographical Variation in Coastal Development (2nd Edition). Longman. London.

Davis G H & Reynolds S J 1996 Structural Geology of Rocks and Regions. John Wiley & Sons, New York.

Dexel J F & Preiss W V (eds) 1995 The geology of South Australia. Volume 2 The Phanerozoic. South Australia Geological Survey Bulletin 54.

Edwards A B 1941 Storm-wave platforms. Journal of Geomorphology 4: 223–236.

Emery K O & Foster H L 1956 Shoreline nips in tuff at Matsushima Japan. American Journal of Science 254: 380–385.

Emery K O & Kuhn G G 1982 Sea cliffs, their processes, profiles and classification. Geological Society of America Bulletin 93: 644–654.

Fairbridge R W 1950 The geology and geomorphology of Point Peron Western Australia. Journal of Royal Society Western Australia 34: 35–72.

Fairbridge R W 1980 The estuary: its definition and geodynamic cycle. *In*: Chemistry and biogeochemistry of estuaries (eds E Olausson & I Cato). Wiley, New York, 1–35.

Fairbridge R W 2004 Classification of coasts. Journal of Coastal Research 20: 155–165.

Fairbridge R W & Hillaire-Marcel C 1977 An 8000-yr paleoclimatic record of the "Double Hale" 45-yr solar cycle. Nature 268: 413–416.

Fairbridge R W & Teichert C 1952 Soil horizons and marine bands in the coastal limestones of Western Australia. Journal and Proceedings of the Royal Society of New South Wales, LXXXVI; 68–87.

Finkl C W 2004 Coastal classification: systematic approaches to consider in the development of a comprehensive system. Journal of Coastal Research 20: 155–165.

Fisk H N 1961 Bar-finger sands of the Mississippi Delta. *In*: Geometry of Sandstone Bodies (eds J A Peterson & J C Osmond). American Association of Petroleum Geologists.

Gallois R W 1965 The Wealdon District. British Regional Geology. Natural Environment Research Council Institute of Geological Sciences.

Gentilli J 1972 Australian Climate Patterns. Nelson, Melbourne.

Geological Survey of Western Australia 1975 The geology of Western Australia. Geological Survey of Western Australia Memoir 2.

Geological Survey of Western Australia 1990 Geology and mineral resources of Western Australia. Geological Survey of Western Australia Memoir 3.

Gill E D 1973 Rate and mode of retrogradation on rocky coasts in Victoria, Australia, and their relationship to sea-level changes. Boreas 2: 143–171.

Ginsburg R N 1953 Beachrock in south Florida. Journal of Sedimentary Petrology: 23: 85–92.

Ginsburg R N (ed) 1975 Tidal Deposits – a Casebook of Recent Examples and Fossil Counterparts. Springer-Verlag, Berlin.

Goudie A & Gardner R 1985 Discovering Landscape in England and Wales. George Allen & Unwin, London.

Guilcher A 1953 Essai sur la zonation et la distribution des formes littorales de dissolution du calcaire. Annales de Geographie 62: 161–179.

Hills E S 1949 Shore platforms. Geological Magazine 86: 137–153.

Hodgkin E P 1964 Rates of erosion of intertidal limestone. Zeitschrift fur Geomorphologie 8: 385–392.

Holmes A 1966 Principles of Physical Geology. Thomas Nelson, London.

Inman D L & Nordstrom C E 1971 On the tectonic and morphologic classification of coasts. Journal of Geology 79: 1–21.

Johnson D P 1982 Sedimentary facies in an arid zone delta: Gascoyne delta, Western Australia. Journal of Sedimentary Petrology 52: 547–563.

Johnson D W 1919 Shore Processes and Shoreline Development. Wiley, New York.

Kay R & Alder J A 1999 Coastal Planning and Management. E & F N Spoon, New York.

Kelletat D H 1995 Atlas of coastal geomorphology and zonality. Coastal Education & Research Foundation Special Issue 13.

Kiernan K 1997 The Conservation of Landforms of Coastal Origin: Conserving Tasmania's Geodiversity and Geoheritage. Forest Practices Unit, Hobart, Tasmania, 273 p.

King C A M 1972 Beaches and Coasts (2nd Edition). Edward Arnold, London.

Klein G D (ed) 1976 Holocene tidal sedimentation. Benchmark papers in Geology Volume 30. Dowden, Hutchinson & Ross, Pennsylvania.

Krumbein W C & Pettijohn F J 1938 Manual of Sedimentary Petrography. Appleton-Century-Crofts, New York.

Logan B W 1974 Inventory of diagenesis in Holocene-Recent carbonate sediments, Shark Bay, Western Australia. *In*: Evolution and Diagenesis of Quaternary Carbonate Sequences, Shark Bay, Western Australia (ed B W Logan). American Association of Petroleum Geologists Memoir 22: 195–249.

Logan B W, Read J F & Davies G R 1970 History of carbonate sedimentation, Quaternary Epoch, Shark Bay, Western Australia. *In*: Carbonate Sedimentation and Environments Shark Bay Western Australia (ed B WLogan). American Association of Petroleum Geologists Memoir 13: 38–84.

Logan B W, Hoffman P & Gebelein C 1974 Algal mats, cryptalgal fabrics and structures, Shark Bay, Western Australia. *In*: Evolution and Diagenesis of Quaternary Carbonate Sequences, Shark Bay, Western Australia (ed B W Logan). American Association of Petroleum Geologists Memoir 22: 140–194.

Lowry D C 1968 Tertiary stratigraphic units in the Eucla Basin in Western Australia. Western Australia Geological Survey Annual Report 1967, 36–40.

Machatschek F 1969 Geomorphology (9th Edition). Oliver & Boyd, Edinburgh. (Edited and translated by H Graul, C Rathjens & D J Davis.).

May V & Heeps C 1985 The nature and rates of change on chalk coastlines. Zeitschrift fur Geomorphologie NF Supplement.-Bd 57:81–94.

Melville R V & Freshney E C 1982 The Hampshire Basin and adjoining areas. British Regional Geology. Natural Environment Research Council Institute of Geological Sciences.

Michel F 1991 Les Cotes de France: Paysages et Geologie. Editions du BRGM, Orleans.

Myers J S 1994 Late Protoerozoic high-grade gneiss complex between Cape Leeuwin and Cape Naturaliste. Geological Society of Australia (WA Division), 12th Australian Geological Convention September 1994, Excursion Guidebook No. 6.

Myers J S 1997 Geology of granite. Journal of the Royal Society of Western Australia 80: 87–100.

Parkin L W (ed) 1969 Handbook of South Australian Geology. Geological Survey of South Australia.

Paskoff R P 2005 Karst coasts. *In*: Encyclopaedia of Coastal Science (ed M L Schwartz). Springer.

Pettijohn F J 1949 Sedimentary Rocks. Harper & Row, New York.

Pettijohn F J & Potter P E 1964 Atlas and Glossary of Primary Sedimentary Structures. Springer-Verlag, New York.

Playford P E 1988 Guidebook to the Geology of Rottnest Island. Geological Society of Australia, Western Australian Division, Excursion Guidebook No. 2.

Playford P E, Cockbain A E & Low G H 1976 Geology of the Perth Basin Western Australia. Geological Survey of Western Australia Bulletin 124.

Reineck H E & Singh I B 1980 Depositional Sedimentary Environments (2nd Edition). Springer-Verlag, Berlin.

Rudwick M J S 1985 The Great Devonian Controversy: the shaping of scientific knowledge among gentlemanly specialists. University of Chicago Press, Chicago.

Sale R, Evans B & McClean M 1989 Walking Britain's Coast: an aerial guide. Unwin & Hyman, London.

Schwartz M L (ed) 1972 Spits and bars. Benchmark papers in Geology Volume 3. Dowden Hutchinson & Ross, Stroudsburg, Pennsylvannia.

Schwartz M L (ed) 1973 Barrier islands. Benchmark papers in Geology Volume 9. Dowden Hutchinson & Ross, Stroudsburg, Pennsylvannia.

Schwartz M L (ed) 1982 Encyclopaedia of Beaches and Coastal Environments Volume XV. Encyclopaedia of Earth Sciences. Dowden Hutchison & Ross, New York.

Schwartz M L (ed) 2005 Encyclopaedia of Coastal Science. Springer, Amsterdam.

Searle D J, Semeniuk V & Woods P J 1988 The geomorphology, stratigraphy and Holocene history of the Rockingham-Becher plain. Journal of the Royal Society of Western Australia 70: 89–109.

Semeniuk C A 1987 Wetlands of the Darling System. a geomorphic approach to habitat classification. Journal of the Royal Society of Western Australia 69: 95–112.

Semeniuk C A 2007 The Becher Wetlands – a Ramsar site: evolution of wetland habitats and vegetation associations on a Holocene coastal plain, south-western Australia. Springer, Amsterdam.

Semeniuk V 1981a Long-term erosion of the tidal flats, King Sound, NW Australia. Marine Geology 43: 21–48.

Semeniuk V 1981b Sedimentology and the stratigraphic sequence of a tropical tidal flat, north-western Australia. Sedimentary Geology 29: 195–221.

Semeniuk V 1985a Development of mangrove habitats along ria coasts in north and northwestern Australia. Vegetatio 60: 3–23.

Semeniuk V 1985b The age structure of a Holocene barrier dune system and its implication for sea-level history reconstructions in southwestern Australia. Marine Geology 67: 197–212.

Semeniuk V 1986 Terminology for geomorphic units and habitats along the tropical coast of Western Australia. Journal of the Royal Society of Western Australia 68: 53.79.

Semeniuk V 1993 The mangrove systems of Western Australia – 1993 Presidential Address. Journal of the Royal Society of Western Australia 76: 99–122.

Semeniuk V 1995 The Holocene record of climatic, eustatic and tectonic events along the coastal zone of Western Australia – a review. Chapter 21 *In*: Holocene Cycles: climate, sea-level rise, and sedimentation (ed C W Finkl). Journal of Coastal Research Special Issue: 17: 247–259.

Semeniuk V 1996a Coastal forms and Quaternary processes along the arid Pilbara coast of northwestern Australia. Palaeogeography Palaeoclimatology Palaeoecology 123: 49–84.

Semeniuk V 1996b An early Holocene record of rising sea level along a bathymetrically complex coast in southwestern Australia. Marine Geology 131: 177–193.

Semeniuk V 2005 Tidal flats. *In*: Encyclopaedia of Coastal Science (ed M L Schwartz). Springer, Amsterdam.

Semeniuk V 2008 Sedimentation, stratigraphy, biostratigraphy, and Holocene history of the Canning Coast, north-western Australia. Journal of the Royal Society of Western Australia 91: 53–148.

Semeniuk V & Johnson D P 1985 Modern and Pleistocene rocky shores along carbonate coastlines, Southwestern Australia. Sedimentary Geology 44: 225–261.

Semeniuk V & Meagher T D 1981 The geomorphology and surface processes of the Australind - Leschenault Inlet coastal area. Journal of the Royal Society of Western Australia 64: 33–51.

Semeniuk V & Searle D J 1986 Variability of Holocene sea-level history along the southwestern coast of Australia – evidence for effect of significant local tectonism. Marine Geology 72: 47–58.

Semeniuk V & Wurm P A S 1987 Mangroves of Dampier Archipelago, Western Australia. Journal of the Royal Society of Western Australia 69: 29–87.

Semeniuk V, Chalmer P N & LeProvost I P 1982 The marine environments of the Dampier Archipelago. Journal of the Royal Society of Western Australia 65: 97–114.

Semeniuk V, Cresswell I D & Wurm P A S 1989 The Quindalup Dunes: the regional system, physical framework and vegetation habitats. Journal of the Royal Society of Western Australia 71: 23–47.

Sharples C 1995 Geoconservation in forest management – principles and procedures. Tasforests 7: 37–50.

Shepard F P 1973 Submarine Geology (3rd edition). Harper & Row, New York.

Shinn E A 1983 Tidal flat environment. *In*: Carbonate Depositional Environments (eds P A Scholle, B G Bebout & C H Moore). American Association of Petroleum Geologists Memoir 33, 171–210.

Shrock R R 1948 A Classification of Sedimentary Rocks. The University of Chigao Press, Chicago.

Snead R E 1982 Coastal Landforms and Surface Features: a photographic atlas and glossary. Hutchinson Ross Publishing, Pennsylvania.

Soper T 1984 A Natural History Guide to the Coast. Peerage Books (in association with the National Trust), London.

Stephenson W J 2000 Shore platforms: a neglected coastal feature? Progress in Physical Geography 24: 311–327.

Sunamura T 1992 Geomorphology of Rocky Coasts. John Wiley & Sons, Chichester.

Trenhaile A S 1974 The geometry of shore platforms in England and Wales. Transactions of the Institute of British Geographers 46: 129–142.

Trenhaile A S 1980 Shore platforms: a neglected coastal feature. Progress in Physical Geography 4: 1–23.

Twenhofel W H 1939 Principles of Sedimentation. McGraw-Hill, New York.

Valentin H 1952 Die Kustern der Erde. Petermann's Geographischen Mittheilungen Erganzungsheft 246.

Wentworth C K 1922 A scale of grade and class terms for clastic sediments. Journal of Geology 30: 377–392.

Wentworth K 1938 Marine bench-forming processes, water level weathering. Journal of Geomorphology 1: 6–32.

White S, King R L, Mitchell M M, Joyce E B, Cochrane R M, Rosengren N J & Grimes K G 2003 Conservation and heritage: registering sites of significance. *In*: Geology of Victoria (ed W D Birch). Geological Society of Australia Special Publication 23. Geological Society of Australia (Victoria Division), 703–711.

Wilson G 1982 Introduction to Small-scale Geological Structures George Allen & Unwin, London.

Woodroffe C D 2002 Coasts – form, processes and evolution. Cambridge University Press, Cambridge.

Journal of the Royal Society of Western Australia, 93: 115–117, 2010

Range extension of the hard coral *Goniopora norfolkensis* (Veron & Pichon 1982) to the south-east Indian Ocean

D Thomson

CSIRO Marine & Atmospheric Research
Floreat, WA, 6014

Manuscript received November 2009; accepted April 2010

Abstract

Two live specimens and *in situ* observation of *Goniopora norfolkensis* in Cockburn Sound south of Perth extends the geographical distribution of this species south by 1250 km and increases the number of coral species described in near-shore Perth waters to 17. The previous southern limit of *G. norfolkensis* in Western Australia was Barrow Island, 150 km west of Karratha. Due to the occurrence of sheltered embayments like Cockburn Sound between Perth and Karratha, *G. norfolkensis* may also be found between these locations. Further southward range extensions might be expected with continuing changes in water temperatures.

Key words: Range extension, *Goniopora norfolkensis*, Poritidae, Cockburn Sound, Barrow Island, Leeuwin Current, Western Australia

Introduction

Cockburn Sound (lat 32° 16'S, long 115° 42'E), located 20 km south of Fremantle, is a semi-enclosed bay 400 km south of the Houtman-Abrolhos Islands, the most southerly coral reefs in the Indian Ocean (Figure 1). Cockburn Sound is dominated by fine soft-sediments with seagrasses, macroalgae and limited low relief (<0.5 m) reef (DALSE 2004). Mean monthly water temperatures range between 15.9 (winter) and 23.0°C (summer), with extremes of 12.8°C (August) and 26.7°C (February) (Hodgkin & Phillips 1969). Winter temperatures are considered too low for the establishment of coral reefs (Veron & Minchin 1992) (<18°C); however, well-developed coral assemblages occur on rubble banks within Cockburn Sound (Veron & Marsh 1988).

Sixteen species of hard corals from 8 genera have been recorded in Cockburn Sound including: *Plesiastrea* (Faviidae), *Goniastrea* (Faviidae), *Cyphastrea* (Faviidae), *Montipora* (Acroporidae), *Turbinaria* (Dendrophyllidae), *Symphyllia* (Mussidae), *Coscinaraea* (Siderastreidae), and *Pocillopora* (Pocilloporidae) (Veron & Marsh 1988). These specimens were found living on rubble banks along the eastern margin of Cockburn Sound, in less than 10 m of water. Species diversity is lower than nearby Rottnest Island (25 species) and the Houtman-Abrolhos Islands to the north (184 species), presumably due to 1) a lower supply of propagules due to the reduced influence of the south-flowing Leeuwin Current (LC) inshore and 2) lower winter water temperatures resulting in greater environmental challenges.

Goniopora spp. inhabit a range of habitats but are most often found in sheltered, turbid reef environments, geomorphologically similar to Cockburn Sound (see Veron 2000). In Western Australia (WA), one species of *Goniopora* has been previously recorded south of the Abrolhos Islands; *Goniopora pendulus* at Rottnest Island (Veron & Marsh 1988). Here we report on three observations of another *Goniopora* species, *Goniopora norfolkensis*, from Cockburn Sound.

Observations

On the 25th of May 2009 one colony of *G. norfolkensis* measuring approximately 450mm (max. diameter, M^1) x 350 mm (perpendicular to max. diameter, M^2) was collected at Jervis Bank, Cockburn Sound (32° 09' 13S 115° 45' 09E). The colony was collected during dredge sampling at a depth of 9 m along with other material including soft sediments, sand dollars, seagrass, holothurians and small pieces of limestone and coral rubble with attached sponges, ascidians and live hard corals. The surface area of the colony of *G. norfolkensis* had approximately 60% live tissue, measuring 330 mm (M^1) x 240 mm (M^2). A section was retained for species identification (Dr John Veron on 11th June 2009) and once identified; the collected specimen was lodged with the WA Museum (WAM Z21482). A further 5 x 200 m dredge sweeps were conducted parallel to the original dredge sweep, however, no additional colonies were collected.

A second colony, measuring 300 mm (M^1) x 250 mm (M^2), was collected during dredge sampling on the 23rd July 2009, 50 m east of the original collection site (Figure 1) at a depth of 8.5 m. The dredge sample contained soft sediments, sand dollars, holothurians and limestone and coral rubble, indicating similar habitat to the previous collection site. The colony had approximately 25% live tissue measuring 120 mm (M^1) x 80 mm (M^2). The colony was placed in flow-through

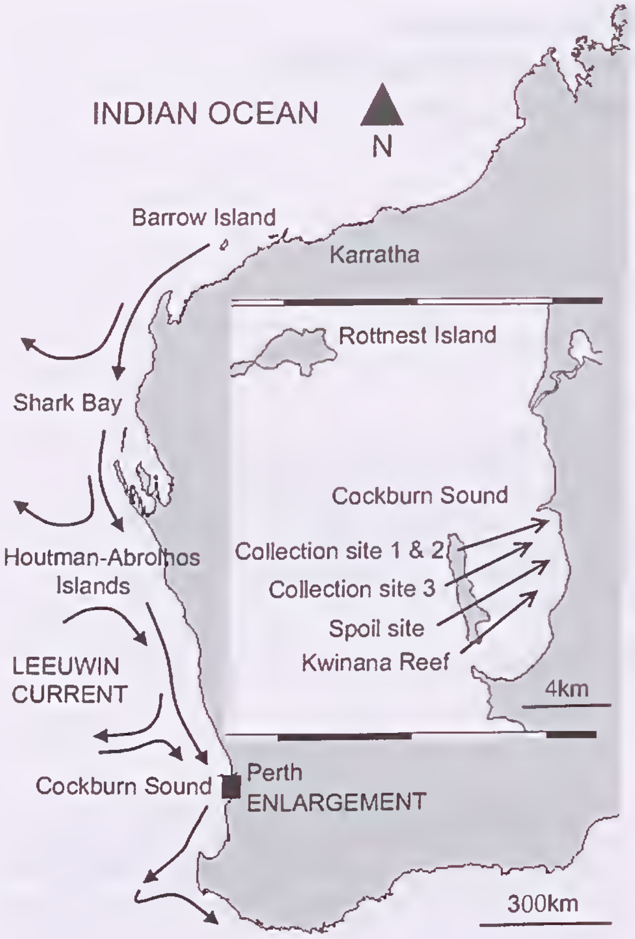


Figure 1. The previous southernmost collection of *G. norfolkensis* was situated 1250km north of Cockburn Sound. INSET The 3 new collection sites located within Cockburn Sound off Perth.

aquaria and a section removed for identification. A further 8 x 200 m parallel dredge sweeps were conducted, however no additional colonies were collected. Two 200 m x 10 m diver surveys were also conducted at this location but no additional *G. norfolkensis* colonies were found. The water temperature at this time was 16°C.

A third *G. norfolkensis* colony measuring 600 mm (M^1) x 400 mm (M^2) was observed by divers on the 5th August 2009, 2.4 km to the south-west of the initial two collection sites (Figure 1). The colony was growing on sandy substratum at a depth of 9.8 m, immediately adjacent to *Posidonia* spp. seagrass (Figure 2). The colony was observed with tentacles extended and the surface area featured almost 100% live tissue. Two further 200 m x 10 m diver surveys were conducted immediately north of the sighting location but no further colonies were found. The observed water temperature was 15°C.

Discussion

It is difficult to determine why *G. norfolkensis* has not been previously observed south of Barrow Island. Its absence from previous collections in Cockburn Sound may be due to a lack of surveys within suitable habitats. For example, Cockburn Sound seagrasses are well documented (Kendrick *et al.* 2002), however, few coral surveys have been carried out (Veron & Marsh 1988). Veron and Marsh conducted the last extensive coral survey in Cockburn Sound in the 1980s, describing extensive coral communities on rubble banks along the eastern margin of Cockburn Sound, however, no *Goniopora* spp. were recorded. Three more recent coral surveys have been conducted at nearby locations: James Point (2 km south), Hall Bank (12 km north) and Kwinana Reef (3 km south) (Figure 1 inset), but areas where *G. norfolkensis* was observed in this study were not surveyed and only hard coral species previously described by Veron & Marsh (1988) were documented.

Alternatively, *G. norfolkensis* may have recruited only recently to Cockburn Sound. Larvae of many organisms are periodically transported as far south as Cockburn Sound (32 °S) via the LC (Maxwell & Cresswell 1981; Beckley *et al.* 2009). The LC is strongest in autumn and winter (Feng *et al.* 2003), coinciding with most broadcast spawning corals in WA releasing larvae (Simpson 1991). Lecithotrophic coral larvae, like those produced by *G. norfolkensis* (Baird *et al.* 2009), can remain competent to settle after 100 d (Graham *et al.* 2008). Numerical-model simulations of WA coastal currents suggest that passive particles may take 50 days to float from Barrow Island (closest known population of *G. norfolkensis*) to the vicinity of Cockburn Sound (Feng *et al.* 2008). Therefore, *G. norfolkensis* larvae may regularly be transported as far south as Cockburn Sound from northern populations when conditions are favourable (*e.g.* strong LC flow).

Changes to local conditions favouring settlement and survival of larvae may also explain a southward range extension of *G. norfolkensis*. Long-term observations (1951–2004) of WA water temperatures show average temperatures have increased 0.6 °C – 1.0 °C from 1951–2004 (Pearce & Feng 2007), and most of this rise occurred in coastal waters south of Barrow Island over the last 20 years (Pearce & Feng 2007). Average surface temperatures at nearby Rottnest Island (13 km west; see Figure 1) increased by 0.68 °C from 1985 and 2004 (Pearce & Feng 2007), suggesting similar trends within Cockburn Sound are likely. Since even small increases in water temperature could favour the settlement and survival of coral larvae at high latitudes, the southward range extension of *G. norfolkensis* to Cockburn Sound may be a direct result of warming observed in WA coastal waters over the last 25 years.

This paper identifies a significant (1250 km) southward range extension for *G. norfolkensis* in WA. This extension could result from inadequate historical sampling, changes in ocean circulation or ocean warming. Since 1) southward range expansions are a possible result of climate change; 2) sea surface temperatures in Australia are predicted to increase by a further 1–2 °C over the next 50 years (Poloczanska *et al.* 2007); and 3) hard corals are good ecological indicators of historical climate change (Greenstein & Pandolfi 2008), monitoring of corals at the edges of their ranges will be essential in assessing benthic communities' responses to climate change.

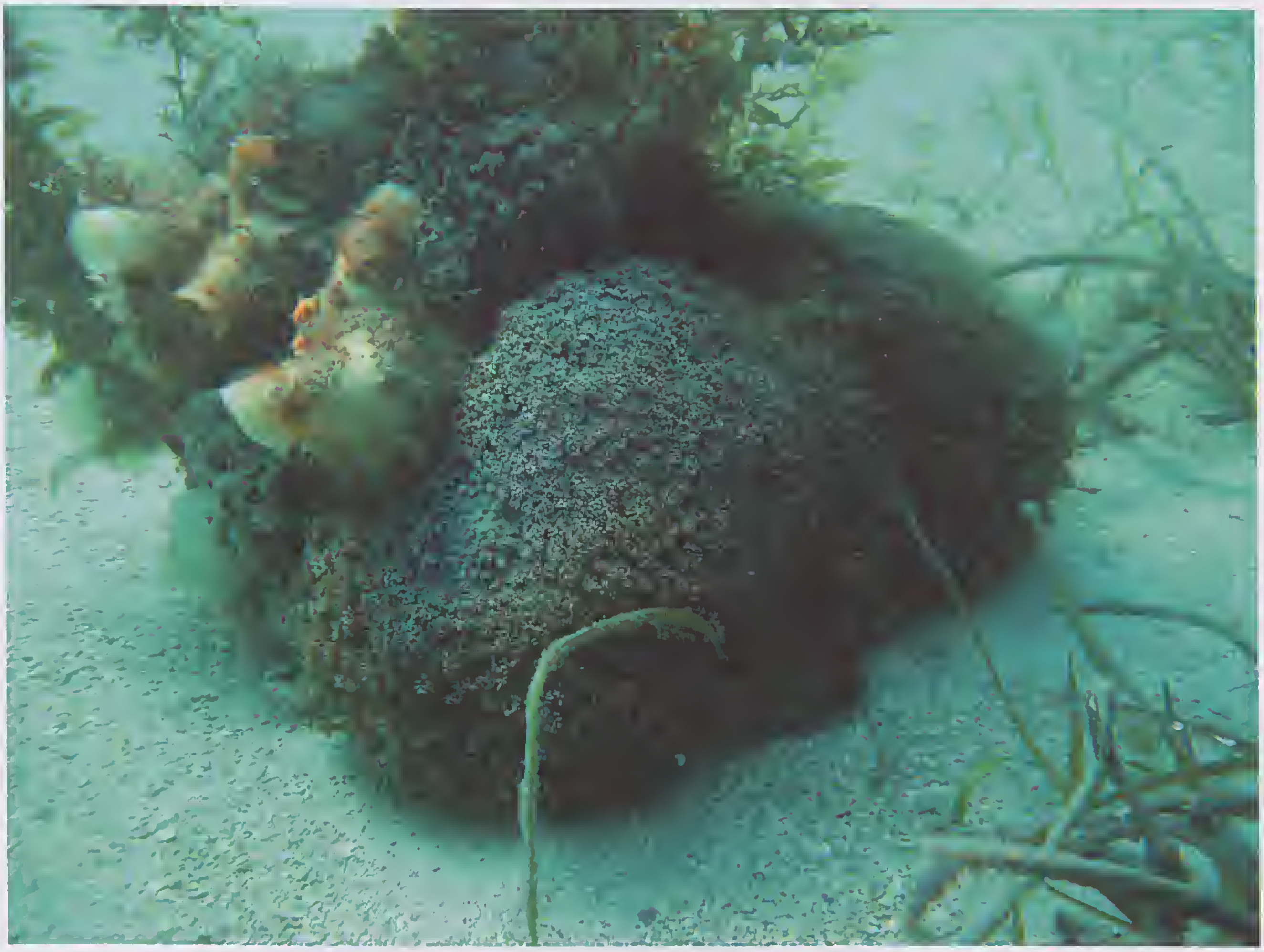


Figure 2. The third colony of *G. norfolkensis* that was found at Cockburn Sound, near Perth. The colony was encrusted with ascidians, sponges and macroalgae and inhabited a sandy substrate adjacent to *Posidonia spp.* seagrass beds.

Acknowledgements: The author thanks J. Fromont, C. Wallace and P. Muir for providing access to Museum records. J Veron for species identification, R. Babcock, F. Graham, D. Bearham, R. Crossing and S. Kondylas for site information and field assistance. M. Feng and D. Slawinski (CSIRO) for running particle tracking simulations and J. Eagle, T. Irvine, K. Cook and two anonymous reviewers for valuable comments on earlier versions of the manuscript.

References

Baird A H, Guest J R & Willis B L 2009 Systematic and biogeographical patterns in the reproductive biology of scleractinian corals. Annual Review of Ecological systems 40: 531 – 571.

Beckley L E, Muhling B A & Gaughan DJ 2009 Larval fishes off Western Australia: influence of the Leeuwin Current. Journal of the Royal Society of Western Australia 92: 101–109.

DALSE 2004 Benthic Habitat Mapping of the Eastern Shelf of Cockburn Sound 2004. Coastal CRC and the University of Western Australia, Perth, WA.

Feng M, Meyers G, Pearce A & Wijffels S 2003 Annual and interannual variations of the Leeuwin Current at 32 degrees S. Journal of Geophysical Research-Oceans 108.

Greenstein B J & Pandolfi J M 2008 Escaping the heat: range shifts of reef coral taxa in coastal Western Australia. Global Change Biology 14:5 13–528.

Hodgkin E P & Phillips B F 1969 Sea temperatures on the coast of south Western Australia. J R Soc West Aust 52(2): 59–62.

Kendrick G A, Aylward M J, Hegge B J, Cambridge M L, Hillman K, Wyllie A & Lord D A 2002 Changes in seagrass coverage in Cockburn Sound, Western Australia between 1967 and 1999. Aquatic Botany 73:PII S0304-3770(0302)00005-00000.

Maxwell J G H & Cresswell G R 1981 Dispersal of tropical marine fauna to the Great Australian Bight by the Leeuwin Current. Australian Journal of Marine & Freshwater Research 32: 493–500.

Pearce A & Feng M 2007 Observations of warming on the Western Australian continental shelf. Marine & Freshwater Research 58: 914–920.

Poloczanska E S, Babcock R C, Butler A, Hobday A, Hoegh-Guldberg O, Kunz T J, Matear R, Milton D A, Okey T A & Richardson A J 2007 Climate change and Australian marine life. Oceanography & Marine Biology Vol 45: 407–478.

Simpson C J 1991 Mass spawning of corals on western Australian reefs and comparisons with the Great Barrier reef. Journal of the Royal Society of Western Australia 74: 85–91.

Veron J E N & Marsh L M 1988 Hermatypic corals of Western Australia. Records and annotated species list. i–vi, 1–136.

Veron J E N & Minchin P R 1992 Correlations between sea-surface temperature, circulation patterns and the distribution of hermatypic corals of Japan. Continental Shelf Research 12: 835–857.

Journal of the Royal Society of Western Australia

A refereed journal for science in Western Australia

Instructions to Authors

The *Journal of the Royal Society of Western Australia* publishes (after refereeing)

- papers and notes dealing with original research done in Western Australia into any branch of the natural or physical sciences;
- papers and notes concerning some aspect of natural or physical science of relevance to Western Australian scientists, but not necessarily done in Western Australia;
- authoritative overviews of any subject in the natural or physical sciences with the general membership of the Society in mind;
- analyses of controversial issues of great scientific moment in Western Australia

Prospective authors of papers in the last two categories should consult the Honorary Editor for further advice. The *Journal* also publishes "Letters to the Editor" and a bibliographic summary of recent journal papers and review articles in "Recent Advances in Science in Western Australia".

Authors are encouraged to submit a list of potential reviewers in Australia or overseas, but choice of reviewers is at the discretion of the Honorary Editor. Publication in the Society's *Journal* is available to all categories of members. Submission of a paper is taken to mean that the results have not been published or are not being considered for publication elsewhere. Authors are solely responsible for the accuracy of all information in their papers, and for any opinions they express. Fifty offprints are provided free to members of the Royal Society of Western Australia; cost of offprints (including Notes) is $100 for non-members.

Manuscripts. The original and three copies must be submitted. They should be printed on opaque white paper with double-spacing throughout and have 3 cm margins. All pages should be numbered consecutively, including those carrying tables and captions to illustrations. Illustrations, both line drawings and photographs, are to be numbered as figures in common sequence, and each must be referred to in the text, in consecutive order. In composite figures made up of several photographs or diagrams, each part should be designated by a letter (*e.g.* Fig. 2B). To avoid risk of damage to the original figures, authors should retain the original figures until the paper is accepted. The copies of the figures accompanying the manuscript must be of good quality. Authors are advised to use the most recent issues of the Journal as a guide to the general format and bibliographic style of the manuscript, and to conform as closely as possible to the style in preparing the manuscript. Authors should maintain a proper balance between length and substance, and papers longer than 10000 words would need to be of exceptional importance to be considered for publication. Electronic processing of manuscripts from disks supplied by the authors is necessary to reduce publication costs. Following acceptance and editing of the manuscript, authors should amend their manuscript and forward one printed copy of the paper and the word-processing file on computer. Preferred format for manuscript files is a doc or rtf file. Templates (rtf and Word2000 format) for manuscripts are available on the Royal Society of Western Australia web page (http://www.rswa.org.au). Manuscripts may also be submitted electronically to rswa_ed@iinet.net.au

Notes. The Society wishes to encourage scientists to publish short notes dealing with original research done in any branch of the natural or physical sciences in Western Australia, or concerning some aspect of natural or physical science of relevance to Western Australian scientists. The objective in publishing Notes is to encourage the dissemination of research findings that might not be enough for a full paper but nevertheless be of interest to other scientists, especially those in Western Australia. In addition, specific aspects of student theses, particular findings of commissioned reports, or isolated observations of significance might be well presented as a one or two page note. Notes will be restricted to a maximum length of two printed pages; notes are particularly sought as these often ensure full use of the pages available in each issue. They should generally have an Abstract, Introduction, Methods, Results and Discussion, and References sections, but the exact section organization is flexible. Photographs and figures should be suitable for single column reproduction (82mm wide) wherever possible. Manuscripts submitted as a Note will be reviewed in the same manner as full articles. Templates (rtf and Word2000 format) for notes are available on the Royal Society of Western Australia web page (http://www.rswa.org.au).

The **Title** should begin with a keyword. The **Abstract** should not be an expanded title, but should include the main substance of the paper in a condensed form. The metric system (S.I. units) must be used. Taxonomic papers must follow the appropriate International Code of Nomenclature, and geological papers must adhere to the International Stratigraphic Guide. Spelling should follow the Concise Oxford Dictionary. **Keywords** or phrases should be provided (maximum of eight, or two printed lines).

References must be set out as follows, with journal titles spelled out in full;

Paper:	Jackson A 1931 The Oligochaeta of South-Western Australia. Journal of the Royal Society of Western Australia 17: 17-136.
Book:	Jacobs M R 1955 Growth Habits of the Eucalypts. Forestry Timber Bureau, Canberra.
Chapter in Book:	Dell J 1983 The importance of the Darling Scarp to fauna. In: Scarp Symposium (ed J Majer). Western Australian Institute of Technology, Bentley, 17-27.

Illustrations. High quality illustrations are required, no larger than 300mm x 400mm, with sans serif lettering suitable for reduction to appropriate publication size (82 or 168 mm wide). Scale must be indicated on illustrations. Photographs must be good quality prints, not exceeding 168mm x 252mm. Colour plates may be published, at the discretion of the Honorary Editor, if these are considered important for clarity or precision of description. Additional printing costs such as those for colour blocks or folding maps may be charged to authors, according to economic circumstances at the time. Please consult the Honorary Editor. It is preferred that figures be also provided as high quality computer graphic files (*e.g.* tif, gif, jpg, cdr or eps files) to ensure high quality reproduction.

Supplementary Publications. Extensive sets of data, such as a large Table or Appendix, may be classed as a Supplementary Publication and not printed with the paper but lodged with the Society's Library (held in the Western Australian Museum, 49 Kew Street, Welshpool, WA 6106) and with the National Library of Australia (Manuscript Section, Parkes Place, Barton, ACT 2600). Photocopies of a Supplementary Publication may be obtained from either institution upon payment of a fee.

Contributions should be sent to:
The Honorary Editor, Journal of the Royal Society of Western Australia
Western Australian Museum, Locked Bag 49, Welshpool DC, WA 6986
or email to rswa_ed@iinet.net.au

Also available from the Royal Society of Western Australia:

(Prices include GST; discount prices for members are in parentheses)

Regular issues of the Journal (price per part)	$12	($8)
The Leeuwin Current: An Influence on the Coastal Climate and Marine Life of Western Australia (Volume 74, 1991)	$20	($15)
Plant Diseases in Ecosystems: Threats and Impacts in South-Western Australia (Volume 77, Part 4, 1994)	$20	($15)
De Laeter Symposium on Isotope Science (Volume 79 Part 1, 1996)	$20	($15)
Symposium on the Design of Reserves for Nature Conservation in South-western Australia (Volume 79, Part 4, 1996)	$20	($15)
Mini-symposium on Remote Sensing and its Applications in Western Australia (Volume 80, part 1, 1997)	$20	($15)
Granite Outcrops Symposium (Volume 80, Part 3, 1997)	$20	($15)
Centennial Issue 1897-1997 (Volume 81, Part 1, 1998)	$20	($15)
Management of Granite Outcrops (Volume 83, Part 3, 2000)	$20	($15)
Leschenault Inlet Estuary (Volume 83, Part 4, 2000)	$50	($35)
Fire and Wetlands on the Swan Coastal Plain (Volume 88, Part 3, 2005)	$20	($15)
Holocene sedimentation, stratigraphy, biostratigraphy, and history of the Canning Coast, north-western Australia (Supplement to Volume 91 Part 1 2008)	$25	($20)
Leeuwin Current Symposium 2007 (Volume 92 Part 2, 2009)	$65	($45)
The Habitats of the Western Australian soldier crab *Mictyris occidentalis* Unno 2008 (Brachyura: Mictyridae) across its biogeographical range (Supplement to Volume 92 Part 3, 2009)	$25	($20)
Symposium on Evolutionary Biology (Volume 92 Part 4, 2009)	$45	($35)

Please add postage and handling at the following rates:

	Australia	Overseas
Regular issue	$5.00	$6.00
Thematic Issues	$6.00	$10.00 (Surface Mail)
The Leeuwin Current: An Influence on the Coastal Climate and Marine Life of Western Australia	$12.00	$18.00 (Surface Mail)
DeLaeter Symposium on Isotope Science	$12.00	$18.00 (Surface Mail)
Granite Outcrops Symposium	$12.00	$18.00 (Surface Mail)
Leschenault Inlet Estuary	$15.00	$30.00 (Surface Mail)
Leeuwin Current Symposium 2007	$12.00	$20.00 (Surface Mail)

Combined postage discounts apply, airmail POA

Please send your order, including payment (all prices in Australian dollars), to:

Honorary Treasurer, Royal Society of Western Australia, c/- WA Museum, Locked Bag 49, Welshpool DC, WA 6986.

The Journal of the Royal Society of Western Australia© is published quarterly by:
The Royal Society of Western Australia, c/- WA Museum, Locked Bag 49, Welshpool DC, WA 6986.
rswa@museum.wa.gov.au
http://www.rswa.org.au

This part was edited by K Meney & M Brocx

Registered by Australia Post — Publication No. PP642409/00008.

Claims for non-receipt of the Journal should be submitted within 12 months of publication, to:
The RSWA Librarian, c/- WA Museum, Locked Bag 49, Welshpool DC, Western Australia 6986,
or email rswa@museum.wa.gov.au
Address changes should be submitted to rswa@iinet.net.au, or
The Hon. Membership Secretary, c/- WA Museum, Locked Bag 49, Welshpool DC, Western Australia 6986.

© ROYAL SOCIETY OF WESTERN AUSTRALIA 2010

This work is copyright. Apart from any use as permitted under the *Copyright Act 1968*, no part may be reproduced by any process without written permission from the President of the Royal Society of Western Australia, c/- WA Museum, Locked Bag 49, Welshpool DC, Western Australia 6986. A permissions line must be provided crediting author(s) and the Journal of the Royal Society of Western Australia as the source.

Published on 17/06/2010

Typeset and printed in Western Australia

Journal of the Royal Society of Western Australia Volume 93 Part 2 June 2010

S-1022